ADVANCEMENTS IN ENERGY ECONOMICS: HISTORICAL PERSPECTIVES, MODELING PERSISTENCE, AND TIME-VARYING COINTEGRATION

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ABSTRACT

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This study explores the historical developments behind climate change and the relationship between clean energy components. To gain a comprehensive understanding of the clean energy sector, a country-specific analysis was conducted for ten countries with the highest levels of clean energy consumption, for the period 1950-2020. International agreements with significant impacts on clean energy have been examined in depth. Unlike previous studies, we analyze two clean energy series, renewable and nuclear energy, separately and comparatively due to their differing sensitivities to external shocks and country-specific approaches. We use the share series of clean energy instead of levels, because the share series represent both environmental considerations and energy efficiency concerns. In the fourth chapter, the study continues with persistence properties of clean energy shares, recognizing that regulatory policies and market instabilities can lead to structural breaks. To address the sign and size asymmetry of series' responses, we employ a modified version of Quantile Unit Root procedures allowing for quantile-specific detection of sharp and smooth break parameters. The study further aims to explore the long-run relationship between emissions and clean energy consumption, in the fourth chapter. In consideration for the impacts of certain events on the long-run relationships, Time-Varying Cointegration methodologies was used, approximating structural breaks as smooth regime changes. We claim that current intergovernmental activities should employ a club-like mechanism, where non-participation incurs penalties. The results indicate that series exhibit stationary behavior upon inclusion of breaks, and asymmetric responses are country-specific. When structural breaks are considered, CO_2 emissions are cointegrated with the shares of clean energy components.

Keywords: Energy Economics, Economic History, Time Series, Long-memory, Time-varying Cointegration

ÖZ

ENERJİ EKONOMİSİNDE GELİŞMELER: TARİHSEL PERSPEKTİF, UZUN HAFIZA ÖZELLİĞİNİN MODELLENMESİ VE ZAMANLA DEĞİŞEN EŞBÜTÜNLEŞME

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Bu çalışma iklim değişikliğinin ardındaki tarihsel gelişmeleri ve temiz enerji bileşenleri arasındaki ilişkiyi incelemektedir. Temiz enerji sektörüne ilişkin kapsamlı bir anlayış kazanmak amacıyla, 1950-2020 dönemi için en yüksek temiz enerji tüketimine sahip on ülke için ülkelere özgü bir analiz yapılmıştır. Temiz enerji konusunda önemli etkileri olan uluslararası anlaşmalar derinlemesine incelenmiştir. Önceki çalışmalardan farklı olarak, iki temiz enerji serisi, yenilenebilir ve nükleer enerji, dış şoklara karşı farklı hassasiyetleri ve ülkeye özgü yaklaşımlar nedeniyle ayrı ayrı ve karşılaştırmalı olarak analiz edilmektedir. Analizde temiz enerji tüketim seviyeleri yerine, temiz enerji kaynaklarının toplam enerji tüketimindeki payları kullanılmaktadır çünkü temiz enerji payları hem çevresel hususları hem de enerji verimliliği kaygılarını temsil etmektedir. Çalışma ikinci bölümde temiz enerji paylarının uzun-hafıza özellikleriyle devam etmektedir. Düzenleyici politikaların ve piyasa istikrarsızlıklarının yapısal kırılmalara yol açabileceği kabul edilmiştir. Çalışmanın önemli katkılarından biri, serilerin dış şoklara verdikleri tepkilerin işaret ve boyut asimetrisini ele alan Kantil Birim Kök prosedürlerinin keskin ve yumuşak yapısal kırılma parametrelerinin her kantil için tanımlandığı şekilde modifiye edilerek kullanılmasıdır. Çalışma üçüncü bölümde karbon salınımı ve temiz enerji tüketimi arasındaki uzun vadeli ilişkiyi araştırmaktadır. Bu amaçla bazı olayların eşbütünleşme üzerindeki etkileri dikkate alınarak, yapısal kırılmaları yumuşak rejim değişiklikleri olarak değerlendiren Zamanla Değişen Eşbütünleşme metodolojileri kullanılmıştır. Çalışma sonucunda, mevcut hükümetler arası iklim faaliyetlerinin, katılmamanın cezayla sonuçlandığı kulüp benzeri bir mekanizma kullanması gerektiğini iddia etmekteyiz. Sonuçlar, serilerin kırılmalar dahil edildiğinde durağan davranış sergilediğini ve asimetrik tepkilerin ülkeye özgü olduğunu göstermektedir. Yapısal kırılmalar dikkate alındığında emisyonlar temiz enerji bileşenlerinin paylarıyla eşbütünleşiktir.

Anahtar Kelimeler: Enerji Ekonomisi, Ekonomi Tarihi, Zaman Serileri, Uzun Hafıza, Zamanla Değişen Eşbütünleşme

To My Sons

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CHAPTER 1

INTRODUCTION

For decades, growing environmental and climate concerns have driven industries toward adopting cleaner and more sustainable energy sources. Innovations have led to the development of cost-effective and convenient methods of energy production, each representing a significant milestone in the journey known as the “Energy Transition”. Although the term is not new, the concept dates back to the 13th century when the initial transition occurred, shifting from wood to coal. However, coal didn't become the primary energy source until the 19th century. The second major transition took place in 1859 with the discovery of oil, marking a shift from coal to oil. Nevertheless, it wasn't until the 1960s that oil became the primary global energy source (Yergin, 2020).

The current phase of the energy transition signifies a major shift away from fossil fuels towards clean energy sources. When we refer to clean energy, we primarily address energy derived from nuclear and renewable sources. Nuclear energy offers the advantage of stable and high levels of energy supply, making it economically appealing. However, concerns about the inherent risks associated with nuclear power have made renewables a more desirable choice from the perspectives of human security and environmental sustainability.

Currently, renewables account for nearly 14% of global primary energy consumption, a substantial increase from around 5% in the 1950s. Meanwhile, nuclear energy contributes to 4% of primary energy consumption, a figure that rose from 0% to 7% between 1950 and 2000, before declining to its current level (BP Statistical Review of World Energy, 2022). In terms of renewable energy, solar photovoltaic (PV) and wind technologies are often referred to as 'modern renewables' because they are seen as more environmentally friendly and industry-compatible, effectively replacing traditional biomass, wood, and hydropower sources (Yergin, 2020). Although the energy transition is gradual and complex, it is undeniably underway. It is predicted that the global electricity generation cannot be entirely renewable, with today's and near future technology and the unreliability of renewable resources. Thus far, the growth of the clean energy industry could not compensate for concerns about energy sovereignty and climate change. The topic preserves political and economic popularity, especially highlighted by the Russian invasion of Ukraine in February 2022. Also, there is a global push towards net-zero carbon emissions, aiming to mitigate climate change. Leading industrial countries like China, the US, and the EU accounting for 76% of emissions today, are pledging to take rigorous actions (UNEP, 2022).

The last phase of the energy transition has been motivated partly by concerns over energy sovereignty and the imperative to mitigate the impact of international energy shocks. Nuclear energy promotion gained importance following the Suez Crisis in 1957 and the oil crisis of the 1970s. While renewables have roots in ancient watermills and windmills, the rapid growth of the renewables industry can be attributed to oil companies hedging against uncertainties in oil supply. Subsequent policies, such as the 1987 Single European Act, played a pivotal role in advancing this transition by diversifying the European energy market. It's worth noting that industry-scale solar and wind technologies did not emerge until the late 19th century.

Recently, environmental concerns gained more emphasis, gradually taking the lead from energy sovereignty. The fight against climate change began in the 2000s, marked by the Kyoto Protocol (1997-2005), which sets country-specific boundaries for lowering GHG emissions. The Paris Agreement (2015) further reinforced global efforts, compelling the United Nations members to work towards limiting global temperature increases to within 2 degrees Celsius in the 21st century. These international agreements, coupled with increasing social awareness, have substantially supported the reduction of energy consumption and the transition towards renewable energy sources. As concerns about the environmental impact of fossil fuels grow, there is an increased emphasis on clean energy alternatives and the composition of energy resources, along with the associated levels of harmful byproducts.

Throughout the transition process, the clean energy sector has undergone significant changes. After the introduction part, the second chapter of this thesis investigates the historical development of clean energy consumption in the ten leading countries in the clean energy industry. The study, covering the period from 1950 to 2020, explores key events and their impact on the sector. This chapter delves into the terms and perspectives of the major international environmental treaties; the Montreal Protocol, the Kyoto Protocol and the Paris Agreement, which have shaped the energy consumption preferences of developed and developing countries. The voluntary nature of these treaties raises doubts about their effectiveness. This study prescribes the global climate convention to design a more functioning treaty that have a club-like nature, as Nordhaus (2020) suggests, where every country wants to join and nobody wants to leave, also in case of non-participation countries should face penalties. The penalties and terms may be tailored for each nation.

In the third chapter, we aim to determine whether shocks to clean energy series result in permanent or transitory effects based on their asymmetric characteristics. When the series shows persistence (long memory), temporary shocks exert long-term effects on moment conditions. Long memory characteristics of energy variables are crucial determinants of policy and business decisions. It is essential to model the series with careful consideration of the nature of structural breaks to have a better understanding of their long-term dynamics. The third chapter contributes to the literature with a modified version of the Quantile Unit Root Test of Koenker and Xiao (2004), incorporating both sharp and smooth breaks in individual quantiles. Unlike the existing studies, we examine the persistence behavior of renewable and nuclear energy shares series separately and comparatively, in a country-specific manner. The study uses data from the countries with the highest levels of clean energy consumption that have lowered their nuclear energy consumption due to security concerns. China and the US are also examined to have better coverage of the distinct responses of leading countries in the sector. Empirical results show a general regression in nuclear energy, while renewable energy is on the rise with fast technological development and lower prices. These findings underscore our suggestion to study the long memory characteristics of clean energy with country- and resource-specific methods. In the long-memory analysis of clean energy, using shares series is enlightening in terms of analyzing the clean energy consumption from an environmentally conscious stand-point since mitigating climate change necessitates a transition in the energy mix from fossil fuels to clean resources, which we will not be able to inspect with the clean energy consumption levels.

The fourth chapter combines the ideas behind the second and third chapters. We concluded that the events in the development path of environmental degradation and clean energy components significantly impact the statistical properties of these series. We ask if climate change and clean energy consumption have long-term relations. To answer this question, we look for the time-varying cointegration (TVC) relation between per capita CO2 emissions and shares of renewable and nuclear energy, using Bierens and Martins' (2010) TVC Test, also considering the impact of economic development levels of countries, measured by per capita GDP. To this date, this relation has not been studied carefully with time-varying cointegration methodologies, considering the distinct patterns of renewable and nuclear energy for each leading country in the clean energy sector. Our results highlight that when time-variation is considered, CO2 emissions are cointegrated with the shares of both clean energy components in all countries. We found evidence that only in China growth of the share of renewables is in a significant negative relation with emissions growth. China has become the leading renewable energy consuming country in only 15 years' time, doubling the renewable consumption levels of the US. Therefore, we claim that coupling climate change mitigation with increasing renewable energy consumption is not impossible benefiting both environment and economic growth.

CHAPTER 2

CLIMATE CHANGE AND ENERGY TRANSITION: A HISTORICAL REVIEW

This chapter explores the historical developments behind climate change and analyzes the relationship between clean energy components - nuclear energy and renewable energy - considering the fundamental differences in countries' clean energy preferences. International agreements with significant impacts on the historical process of clean energy have been examined in depth, and their effectiveness has been assessed comparatively. The study concludes that each country exhibits different choice behaviors regarding its energy consumption mix.

Analyzing clean energy as a single variable that combines renewable and nuclear energy is problematic because each source serves as a substitute not only for traditional fossil fuels but also for each other. These substitution effects are also country-specific. While progress has been made in line with environmental policy objectives, the developments are not yet sufficient. Innovative approaches are needed to achieve desired outcomes, addressing both environmental degradation and economic development. Current intergovernmental activities should employ a Club-like mechanism, where the incentives for participation outweigh the costs of compliance, and non-participation incurs penalties.

2.1. Introduction

One may consider clean energy in terms of its environmental benefits. However, the major turning point following the 1970s Oil Crisis, which initiated the increase in clean energy consumption, was driven by energy sovereignty rather than environmental concerns. This focus on energy sovereignty continued to drive increases in clean energy consumption until the 2000s. Following the Kyoto Protocol in 1997, clean energy consumption accelerated, with most of the increase in the 2000s coming from renewable resources.

During the 1990s, countries approached nuclear energy with suspicion after the Three Mile Island accident in 1979 and the Chernobyl accident in 1986. Consequently, nuclear energy did not regain its initial momentum, and the Fukushima nuclear disaster in 2011 further intensified hesitancy. Countries such as Japan and Germany canceled their nuclear programs, and many others froze or slowed the growth of nuclear energy. We have observed that intergovernmental environmental treaties primarily encourage renewable energy consumption, while nuclear energy consumption has remained low for at least the last two decades.

The 2000s marked a period where collective efforts toward climate change mitigation were among the top international concerns. Countries provided solutions to the environmental crisis, with no major conflicts except for the 2008 economic crisis and the Covid-19 pandemic. These events led to a recession in industrial and economic growth, coupled with a reduction in GHG emissions due to lower economic activity. This impact was temporary as economies recovered. Some argue that the economic slowdown during these times shifted the focus toward economic growth, relegating environmental concerns. Nevertheless, the need to cut GHG emissions and promote clean energy remained a central solution to the climate crisis, demonstrating that it is possible to address environmental issues without hindering economic growth.

In recent years, the focus on energy transition and increased clean energy consumption has shifted slightly from an environmental perspective back towards energy sovereignty. This shift followed the energy crisis faced by European countries due to the Russian invasion of Ukraine in February 2022. Additionally, geopolitical risks in the Middle East, a region accounting for more than one-third of the world’s seaborne oil trade, has put oil markets on edge following the war in Gaza started in October 2023. Disruptions in natural gas markets, including the production cuts in Israel because of the state’s focus on Gaza, the labor strike risks in Australia threatening 10% of global LNG supply from August on, and the damage to a key pipeline in the Baltic, detected around October in 2023 highlighted the need for alternatives to conventional resources. The reluctance toward nuclear energy has started to fade due to the urgent need to replace fossil fuels rapidly.

The first UN Conference on Human Environment in 1972 in Stockholm highlighted sustainable development but did not focus on clean energy sources. By 1992, the UNFCCC subtly addressed the need for clean energy under the energy efficiency agenda. Environmental issues and energy transition became closely linked with the commitments of the Kyoto Protocol (2005) and the Paris Agreement (2015).

At COP28 (Conference of the Parties) in 2023, to keep the 1.5°C target within reach, the summit put forward five objectives:

1. Support the tripling of renewable energy capacity by 2030.
2. Aim to double the rate of global energy intensity improvements by 2030.
3. Ensure the orderly decline of the use of fossil fuels.
4. Recognize that scaled-up investment is required.
5. Highlight the critical role of, and opportunity for, the fossil fuel industry to reduce methane emissions from their operations, to cut them by 75% by 2030.

All five objectives emphasize the efficient allocation of energy resources to mitigate climate change.

Thus, we aim to provide a historical analysis of clean energy in the context of climate change to understand future directions. We believe in the value of such studies in providing a clearer picture of the development of the clean energy sector. The remainder of the study is organized as follows: Section 2.2 examines international environmental efforts closely linked to energy transition. Section 2.3 introduces our dataset and presents historical trends in nuclear and renewable energy from 1950 to 2020, both regionally and for specific countries with the highest clean energy consumption. The concluding section summarizes our findings and provides a discussion and conclusion.

2.2. Intergovernmental Climate Change Treaties

Following the events in the late 20th century, countries began recognizing the severity of climate change concerns and initiated discussions and planning for collective action. It became clear that individual efforts were insufficient to confront climate change effectively. Governmental action and international collaboration were deemed necessary. Consequently, in 1968, the UN delivered a report titled “Activities of United Nations Organizations and Programmes relevant to the human environment: report of the Secretary-General,” calling for the first environmental conference and warning that continued trends could endanger life on Earth.

2.2.1. UN Conference on the Human Environment, June 1972

The Stockholm Conference on the Human Environment is regarded as the first step towards developing international environmental law. The conference primarily focused on the environmental impact on human health, addressing anthropogenic (human-induced) harms such as overconsumption and forest degradation. The term “energy” first appeared in Recommendation 57, which called for methods to measure and collect data on the environmental impact of energy use. Recommendation 58 advocated for information exchange on energy topics, while Recommendation 59 highlighted the need for a basis to develop energy resources effectively, considering their environmental effects (United Nations, 1972).

Beyond this limited focus on energy, the conference also addressed radioactive waste management related to nuclear energy. The International Atomic Energy Agency actively participated and was expected to take action on many post-conference operations.

The 1972 Stockholm Conference led to the establishment of the United Nations Environment Programme (UNEP). In collaboration with the International Maritime Organization, UNEP’s first initiative was the 1973 Convention for the Prevention of Pollution from Ships. The same year saw the signing of the Convention on International Trade in Endangered Species of Wild Fauna and Flora, regulating the trade of approximately 38,000 species. Subsequent conventions and programs, such as the Regional Seas Programme (1974), the Convention on Migratory Species (1979), and the Water for Life Decade (1981), focused on species protection and methods for cleaning environmental elements, including water and air, by controlling pollution sources like oil spills.

2.2.2. Montreal Protocol, 1987

As global attention on the environment increased, a 1974 study by Molina and Rowland demonstrated that Chlorofluorocarbons (CFCs) accumulating in the stratosphere could be broken down by UV radiation, releasing chlorine atoms that deplete the ozone layer. This scientific evidence prompted immediate action, with the US, Canada, Sweden, and Norway banning CFCs in pressurized cans. In 1985, Farman et al. discovered the overall thinning of the ozone layer, and it was found that a hole in the ozone layer above Antarctica had grown to the size of the US (Sunstein, 2006). These developments led to the Vienna Convention for the Protection of the Ozone Layer in 1985 and the signing of the Montreal Protocol in 1987 by 43 countries. Despite resistance from industries using CFCs, the protocol became the first UN treaty to achieve universal ratification as of 2022.

Chlorofluorocarbons (CFCs) and other substances deplete the ozone layer, hence they are termed Ozone Depleting Substances (ODSs). The thinning and hole in the ozone layer allowed UV light from the sun to reach the earth, warming the earth’s surface and causing droughts and harm to living species, as well as UV-induced disorders such as skin cancer and ocular diseases.

The Montreal Protocol focuses on controlling ODS use through reporting, national licensing, and trade quotas, aiming for a progressive phase-out of these substances across all industries, except for critical uses like asthma inhalers. It is regarded as the most successful global environmental treaty, with 198 countries ratifying it and significant positive outcomes recognized.

The Protocol has been continuously revised, adding new substances like Hydrofluorocarbons (HFCs) through the Kigali Amendment in 2016, and increasing commitments from countries. It has been adjusted six times and amended four times. The ozone layer has already begun healing, with expectations of full recovery in most parts by 2040 and the Antarctic hole by 2066.

The Montreal Protocol also has a beneficial side effect beyond ozone protection, as many ODSs are also greenhouse gases. The Protocol is anticipated to contribute to global warming prevention efforts, potentially lowering the increase in surface temperatures by 0.5-1°C by 2050. Recently, the focus of the Protocol has increasingly shifted from ozone protection to climate change mitigation. The success of the Protocol is attributed to its firm trade sanctions and robust enforcement mechanisms (Heath, 2017).

2.2.3. UN Conference on Environment and Development, June 1992

By 1987, the World Commission on Environment and Development initiated discussions on sustainable development with its comprehensive report, “Our Common Future.” This marked the beginning of conversations about the relationship between the environment and energy resources.

The Rio Conference emphasized the connection between economic growth, consumption, and GHG emissions, highlighting the environmental harm caused by these activities. The primary reasons for the accumulation of greenhouse gases (GHGs) in the atmosphere are the burning of fossil fuels and deforestation. High concentrations of GHGs trap heat, preventing it from escaping into space, which leads to climate change manifesting as heatwaves, wildfires, storms, droughts, and melting ice caps.

Climatic changes significantly impact ecosystems, disrupting the lifecycles of all flora and fauna. As humans depend on the environment for resources, this accelerating change will have profound and evident effects on human life. This is likely why the first conference on the environment was titled the "Conference on the Human Environment." The immediate consequences are clear: increased heat affects the cardiovascular system, air pollution impacts the respiratory system, famine affects nutrition, and drought leads to water scarcity and water-borne diseases. Additionally, rising sea levels and natural disasters can devastate residential areas, leading to climate migration issues.

The Rio Summit is notable for establishing the United Nations Framework Convention on Climate Change (UNFCCC) in 1994. The 198 countries that have ratified the convention are known as Parties to the Protocol. The UNFCCC prioritizes developed countries, holding them responsible for the majority of greenhouse gas (GHG) emissions until the 1990s and addressing them to make the largest emissions reductions. These developed nations, referred to as Annex II countries, include 20 OECD members: Australia, Canada, Iceland, Japan, New Zealand, Norway, United Kingdom, USA, Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, Netherlands, Portugal, Spain, and Sweden. Although the US initially took a leading role in supporting the UNFCCC, concerns over low commitment from developing countries and the burden placed on the US led to its rejection by the US Senate. Australia also did not participate in the UNFCCC. Consequently, Annex II comprises all developed countries except the US and Australia. In addition to their efforts to mitigate climate change, Annex II countries are required to fund climate change activities in developing nations and share environmentally friendly technologies (UNFCCC, 1992).

Annex I countries include all 38 OECD countries plus economies in transition (EIT), which include Russia, Baltic countries, some Central and Eastern European states, and Botswana from Africa. Annex I countries must report regularly, on a yearly basis, to the convention and submit data on their GHG emissions, using 1990 as the base year. Non-Annex I parties are the developing countries that have ratified the convention and are required only to report every four years (UNFCCC, 1992).

Initially, the UNFCCC faced resistance from participating countries because the consequences of climate change were perceived as vague. However, scientific reports and assessments supported by the convention helped achieve global acceptance of the main idea: “the mitigation of emissions to fight climate change.”. Another reason for resistance to the UNFCCC was that the convention did not hold developing countries responsible for future emissions cuts. This decision was based on the fact that today’s developing countries did not contribute significantly to emissions during the industrialization period before 1990. Furthermore, the convention anticipated that GHG emissions would rise in developing countries as they industrialized. Although controversy around this topic persisted, the concept of emission permissions for developing countries was later emphasized by the Kyoto Protocol in 1997, which introduced mechanisms like the Clean Development Mechanism. Subsequent developments led to the Paris Agreement in 2015, a “middle ground” treaty addressing these issues.

2.2.4. The Kyoto Protocol, December 1997

The initial major global climate treaty under the UNFCCC is the Kyoto Protocol. The process from its adoption to its entry into force spanned from 1997 to 2005. The title of the protocol, “Kyoto Protocol to the UNFCCC,” signifies its role in operationalizing the UNFCCC by setting country-specific targets for emission reductions. The first commitment period of the Protocol is binding only for developed nations, Annex II countries, as they were primarily responsible for increasing GHG emissions until then. For the first commitment period (2008-2012), carbon equivalent emission targets for six GHGs (Carbon dioxide (CO2), Methane (CH4), Nitrous oxide (N2O), Hydrofluorocarbons (HFCs), Perfluorocarbons (PFCs), and Sulphur hexafluoride (SF6)) were assigned to each country. The Kyoto Protocol focuses on emissions not regulated by the Montreal Protocol.

These carbon emission targets are called carbon-caps. The aggregate reduction target for the first period was 5% compared to 1990 levels. After Canada withdrew in 2011 and Japan and Russia decided not to ratify the Protocol after the first period, the second commitment period (2013-2020) saw changes in both country participation and the listed GHGs. The reduction target for the second period was updated to 18% from 1990 levels.

The Protocol requires ratified parties to implement and elaborate policies to enhance energy efficiency, promote renewable energy, enhance GHG reservoirs through sustainable forest management, promote sustainable agriculture, develop carbon dioxide sequestration technologies, and adopt environmentally sound technologies. It also aims to reduce market imperfections by using market instruments such as fiscal incentives and tax exemptions in all GHG-emitting sectors. Cooperation among ratified countries is essential for knowledge and financial flow in the form of funding, insurance, and technology transfers (Kyoto Protocol, 1997).

Annex I countries are required to submit annual inventories of emissions and sinks in their "national communication," expected every year. The timeline for submissions is determined by the Parties to the Protocol. Expert review teams, composed of individuals nominated by Parties to the Protocol and intergovernmental organizations, prepare technical assessment reports.

The Intergovernmental Panel on Climate Change and the Subsidiary Body for Scientific and Technological Advice constantly re-estimate and revise the impact of GHGs on global warming. Each country reviews its targets based on these organizations' work. Reports are reviewed by the convention's secretariat and by each party through the Conference of Parties (COP), which acts as a decision-making body for the Protocol's implementation. The COP has met annually for the past 28 years since 1995, with the latest meeting being COP28 in 2023.

The highest emissions target percentage is allowed for Iceland, committed to reaching 110% of its 1990 carbon equivalent emissions. The lowest allowed percentage is 92%, committed by most Annex II countries, meaning they must reduce their emissions by 8%. Norway, Australia, and Iceland are the countries allowed to increase their emissions among Annex I countries.

The Kyoto Protocol highlighted the primary role of energy in climate change mitigation. Recommendations in Article 2 start with "the enhancement of energy efficiency in relevant sectors of the national economy" and include "promotion, research, development, and increased use of new and renewable forms of energy." Article 10 mentions energy programs first as the regional programs to be implemented. Annex A lists the GHGs and sectors controlled under the Protocol, with energy being the primary sector. The Protocol has three flexibility mechanisms to maximize parties' options for emissions control: Emissions Trading (ET), the Clean Development

Mechanism (CDM), and Joint Implementation (JI). These mechanisms facilitate the transfer of emission units between parties, enhancing the Protocol's effectiveness.

Emissions Trading (ET) applies only to developed countries. If one party exceeds its emissions reduction target while another fails to meet its commitment, the party with spare emissions units can transfer these units to the party that did not meet its target. Additionally, parties in a region can form a group to collectively decide on an emission target for the region, working together towards the aggregate reduction target. However, if the region does not meet the aggregate target, each country remains responsible for its individual goals (Kyoto Protocol, 1997).

The Clean Development Mechanism (CDM) allows for cooperation between a developed country in Annex I and a developing country in non-Annex I. If a developed country cannot reduce its GHG emissions to the committed levels within its borders, it can help a developing country reduce its GHG emissions through clean infrastructure projects such as solar or wind farms. The developed country then acquires carbon credits that count towards its GHG emissions inventory (Kyoto Protocol, 1997). This mechanism has significantly contributed to the development of renewable energy industries, particularly in Asia (Grubb, 2016).

Joint Implementation (JI) is similar to the CDM but operates exclusively among developed countries (Annex I). This mechanism allows developed countries to invest in emissions reduction projects in other developed countries and receive carbon credits in return (Kyoto Protocol, 1997).

Kyoto’s flexibility mechanisms - ET, CDM, and JI - involve uncertainties in reliability, costs, and permanence. Concerns exist about the quality of the reductions and removals sold. For example, the value of a CDM project is often calculated theoretically. Typically, the real contribution of the project to lowering carbon emissions is unknown, but its credits are issued for the investing country's emissions inventory before the project has even started. Another concern is double counting. In principle, carbon credits from climate projects in another country should be included in the investing country’s inventory. However, emissions reductions from these projects are usually counted in the inventories of the recipient countries as well. Additionally, using traded carbon credits to offset more domestic emissions often delays the reduction of domestic emissions (Climate Action Tracker, 2023).

Several other arguments critique the mechanisms and terms of the Kyoto Protocol. While the Protocol aims to operationalize the UNFCCC and is a legally binding treaty, there are no practical penalties for unmet commitments. It remains a political agreement in principle among the Parties to the Protocol. The Protocol establishes a framework for review and reporting, recommends implementing climate change mitigation projects, and commits Parties to individual emissions targets. The Protocol’s Enforcement Branch has specific roles in accounting for emissions commitments. One role is suspending parties that fail to meet their carbon-caps within the commitment period from eligibility for flexibility mechanisms. Another role involves transferring any excess emissions to the next commitment period multiplied by a factor of 1.3 (UNFCCC, 2009). However, this means a country can continuously transfer excess emissions to subsequent periods without ever meeting its targets. Moreover, countries can withdraw from the Protocol, as Canada did just before the first commitment period ended.

Apart from the ambiguity of the terms and conditions of the Protocol, the initial reluctance of countries to participate was partly due to the unconvincing claims of the UNFCCC about the environmental crisis. The international community demanded clear outcomes of climate change. Uncertainty analysis, such as the one by Webster et al. in 2001, helped clarify this. They projected an expected surface temperature increase of 2.3°C with a 95% confidence interval of 0.9°C to 5.3°C. The distribution was skewed right, indicating a higher probability of exceeding the mean than remaining below it. Advances in climate science provided a stronger foundation for the UNFCCC's claims, leading to the acknowledgment of climate change impacts.

The non-ratification of the US was a significant failure for the Kyoto Protocol from the outset. In 1997, when negotiations began, the US was the primary polluter, contributing around 30% of global emissions since the base year, 1990, while China's share was just 6%. With China's rapid growth and collective emissions reaching around 10%, its annual emissions surpassed those of the US by 2006, shortly after the first commitment period began (Global Carbon Budget, 2023). Consequently, the Protocol's arguments became outdated for the US, which did not want to bear most of the burden from the start (Gregg, 2008).

The Protocol was perceived as ineffective, particularly by the US, because it allowed developing countries to pollute without limits while restricting developed countries. This imbalance made it clear that climate change could not be slowed down effectively. Despite being a main actor throughout the UNFCCC process, the US found the terms of the Kyoto Protocol disadvantageous. The Senate decided that if the US would lose more than it gains, it would not participate, and they acted accordingly (Sunstein, 2006).

There is an ongoing debate about whether the second commitment period of the Kyoto Protocol was legally binding or merely voluntary. This second period, known as the Doha Amendment to the Kyoto Protocol, covered the timeline from 2013 to 2020. For the amendment to be binding, it required ratification by all parties to the Protocol. By 2015, only 31 out of 144 countries had ratified the second period. The second commitment legally entered into force with the ratification of 144 parties, just at the end of the commitment period. Therefore, the commitments of the second period are indeed binding but the Doha Amendment led to a stall for the Kyoto Protocol as the ratification process took the entire commitment period (Erbach, 2015). It remains uncertain whether there will be a third period for the Protocol.

2.2.5. The Paris Agreement, 2015

The Paris Agreement is the second major treaty under the UNFCCC, aiming to limit global surface temperature increases to well below 2°C, with an aspiration of 1.5°C. Within this agreement, 186 countries, responsible for 90% of global emissions, have submitted carbon reduction targets known as Nationally Determined Contributions (NDCs). These emission targets are country-specific, taking into account each country's capabilities, level of development, and historical contributions to emissions. Each country plays a primary role in setting its NDCs.

The Agreement mandates transparency and accountability from all participants through monitoring, verification, and public reporting of progress towards individual reduction targets and the 1.5°C goal. This system encourages compliance through peer pressure rather than financial penalties. Annual COP (Conference of the Parties) meetings, similar to those of the Kyoto Protocol, facilitate the submission of mandatory NDCs and non-mandatory long-term strategies for more ambitious efforts. Although not explicitly stated in the formal documents of the Paris Agreement, and with no official move to replace the Kyoto Protocol, the Paris Agreement is seen as the successor of Kyoto in the climate change mitigation efforts. The commitment period of the Paris Agreement began in 2020, immediately following the end of the Kyoto Protocol’s second commitment period. A third commitment period for the Kyoto Protocol has not been decided upon, even though it has been four years since the end of the second period.

Different from the Kyoto Protocol’s mechanisms, the Paris Agreement allows for the compliance of a top-down and a bottom-up approach. In the top-down approach, the Agreement imposes the 1.5°C target on all participating countries. In the bottom-up approach, all parties state their intended NDCs. The Agreement assesses the NDCs, questioning if total contributions meet the 1.5°C target. If not, the countries are required to revise their NDCs.

The Paris Agreement introduces more stringent regulations in trade and carbon crediting under Article 6.2 and 6.4 than the Kyoto Protocol's ET, CDM, and JI mechanisms. This time, all participating countries are target countries, without any segregation as in Kyoto’s Annex I and Non-Annex I countries. Article 6.2 allows countries to use internationally transferred mitigation outcomes (ITMOs) to achieve their NDCs. ITMOs can be used through international linking of emission trading schemes, crediting mechanisms, or direct bilateral transfers. Article 6.4 establishes the new crediting mechanism under the authority and guidance of the Conference of the Parties (Schneider and Broekhoff, 2016).

Compared to the Kyoto Protocol, the Paris Agreement places more emphasis on overall mitigation in global emissions and environmental integrity. Environmental integrity means that the total outcome of country-level NDCs, combined with overall ITMOs, should not result in higher global emissions. This can be achieved through more ambitious NDCs, transparency, and robust accounting to avoid double counting, ensuring real, measurable, and long-term mitigation benefits. Sustainable development is also emphasized throughout all mechanisms (Schneider and Broekhoff, 2016).

As the Kyoto Protocol was considered a failure, the Paris Agreement seeks to address its shortcomings and draws attention to the “ambitions gap” by the governments of the parties to the UNFCCC. “Ambitions” refer to all policies and regulations that result in lowering GHG emissions and mitigating climate change. It is stated that, to achieve the 1.5°C goal by the end of the 21st century, global ambitions should be quadrupled from today’s levels. The Paris Agreement has led to some achievements in terms of increasing ambitions, especially for high-income countries (IRENA, 2023).

Closing the ambitions gap requires identifying areas where improvements can be achieved through policy implementation. It is found that 72% of emissions are still energy-related. Thus, there is a significant climate mitigation opportunity in the energy field. To close the ambitions gap, the Agreement focuses on decarbonizing power generation through renewables, nuclear energy, and carbon-capture technologies in fossil power processes; electrifying energy use in buildings, factories, and vehicles; and supporting energy conservation (Black et al., 2023).

Building on the goal of closing the ambitions gap, the Paris Agreement places more emphasis on CO2 removals compared to the Kyoto Protocol's focus on emission reductions. Removals are achieved through clearing the soil and atmosphere of existing GHGs. For instance, some removal technologies, like afforestation, reforestation, and biochar, use carbon in the photosynthesis process, lowering the density of carbon in the atmosphere. The number of publications on CO2 removal technologies grew exponentially following 2015, demonstrating the impact of the Paris Agreement on this topic (Terlouw et al., 2021).

After COP28 in 2023, current policies and precautions against climate change are expected to result in a 2.7°C increase in global surface temperatures by 2100. Even if intended NDCs were thoroughly applied, the expected increase would be 2.5°C. These scenarios are still far from meeting the Paris Agreement target of 1.5°C. According to the Climate Action Tracker (CAT) thermometer, a better scenario at 2.1°C can be achieved if non-mandatory long-term binding targets are applied. The most optimistic scenario could lower the temperature rise to 1.8°C with all announced targets, NDCs, and net-zero targets (Climate Action Tracker, 2023).

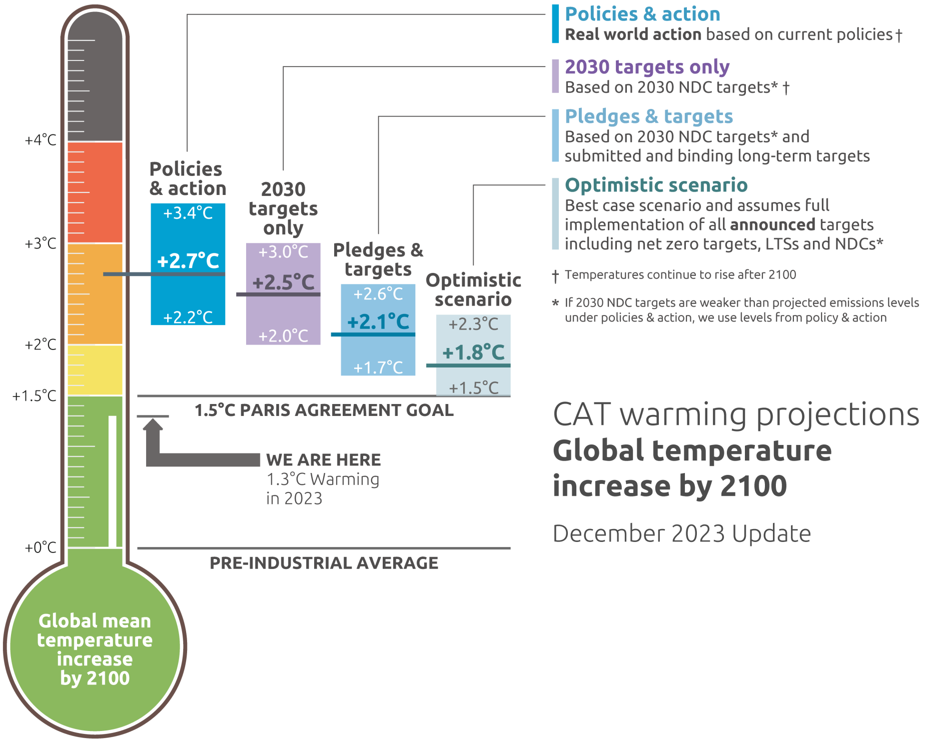

Figure 2.2.1 The CAT Thermometer[1]

Source: Climate Action Tracker (2023). The CAT Thermometer. December 2023. Available at: https://climateactiontracker.org/global/cat-thermometer/ Copyright © 2023 by Climate Analytics and NewClimate Institute.

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[1] Climate Action Tracker is an independent scientific project that tracks government action through climate policies, NDCs and comparability of individual countries' efforts against their fair share in the global conventions and agreements. CAT has been providing this information since 2009.

It appears in Figure 2.2.1 that the temperature increases projected by the Climate Action Tracker (CAT) have decreased over time. The 2018 report predicted a 3.3°C rise in surface temperatures, while the 2023 report forecasts a 2.7°C rise. This suggests that emerging policies are making a positive impact, offering hope for mitigating climate change (Climate Action Tracker, 2018). The Paris Agreement resulted in a collective decision by all countries for a fossil fuel phase-out, in principle. The phase-out is essential for limiting temperature rises to targeted levels. However, there are concerns that without rigorous action, these targets may not be achieved. Current targets such as "phasing-down fossil fuels" or "decreasing emissions from fossil fuels" appear insufficient given the current trajectory (Climate Action Tracker, 2023).

2.2.6. Comparison of Three Climate Treaties

All 198 Parties to the Montreal Protocol are also parties to the UNFCCC. However, only 192 out of 198 are parties to the Kyoto Protocol (non-parties are the US, Canada, Andorra, Holy See, Palestine, and South Sudan), and 195 out of 198 are parties to the Paris Agreement (non-parties are Iran, Libya, and Yemen). It is debated whether the success of the Montreal Protocol can be replicated for reducing GHG emissions. The likelihood is low because the use of ODSs was limited to a few industries such as air conditioning, refrigeration, and pressurized cans, and replacements for these substances were readily available. In contrast, GHG emissions are caused by the widespread use of fossil fuels across all industries. Even if clean alternatives like renewables and nuclear energy exist, the transition is time-consuming and requires significant lifestyle changes from all economic agents.

Table 2.2.1 summarizes the main differences between the most effective environmental treaties. The following text delves into more detail on how the characteristics of each treaty have influenced their impact on the climate change mitigation process. We aim to gain insights into which methodologies are effective in mobilizing the international community toward a common goal.

The Montreal Protocol benefits from having a well-defined objective - "preventing ozone depletion" - with clear and immediate consequences of noncompliance, such as increased skin cancer rates. These tangible and easily understood harms are more likely to influence behavior and prompt swift action (Sunstein, 2006). In contrast, the climate crisis represents a broader issue with potentially catastrophic global events occurring over the long term. Given that humans are often myopic and tend to discount future outcomes, the present value of long-term consequences is low (Brown and Lewis, 1981). However, despite the gradual progression of global warming, without effective mitigation efforts, it may become irreversible.

Table 2.2.1 Comparison of the most effective environmental treaties

	Main Purpose	**Substances Controlled**	**Actions and Sanctions**
Montreal Protocol	Preventing Ozone Depletion	ODSs	• Monitoring and Reporting • Financial and Technical Support • Trade quotas and licensing • Targets developed countries more. Developing countries needs to comply with same conditions in a longer timeline.
Kyoto Protocol	Reducing GHG emissions to mitigate climate change	GHGs	• Monitoring and Reporting • Financial and Technical Support • Flexibility Mechanisms: CDM, JI and IET • Targets developed countries. • Legal Obligations (Ineffective) • Common metrics
Paris Agreement	Limiting Global Surface Temperature Rises below 1.5ºC by 2030 to mitigate climate change	GHGs	• Monitoring and Reporting • Financial and Technical Support • Flexibility Mechanisms: Articles 6.2 and 6.4: more focus on Transparency, Accounting and Environmental Integrity • Bottom-up NDCs and long-term strategies both for developed and developing countries along with the top-down 1.5ºC target. • Focus on closing the ambitions gap

Most governments cannot take action for fear of sacrificing economic growth and weakening their political standing. The short timeline between election periods does not allow governments to take rigorous steps. There may be a need for politically neutral climate institutions in each country that follow up on the correct steps for climate change mitigation without interruption. Currently, most of the responsibility lies with non-governmental organizations and the private sector.

Furthermore, there is a view that the Montreal Protocol and Kyoto Protocol may inadvertently undermine each other's effectiveness. The Montreal Protocol indirectly encourages the emission of substances controlled by the Kyoto Protocol and vice versa (McCabe, 2007). Thus, complying with one protocol more may make the other less successful. Progressive adjustments and amendments to both protocols may have resolved such conflicts of interest over time. However, it is possible that the success of the Montreal Protocol has led to the widely accepted failure of the Kyoto Protocol, at least for the first two commitment periods.

The stance of developing nations has been a controversial issue for each treaty. All the treaties recognized that developed countries, with around 25% of the world's population, are responsible for almost 90% of the pollution. In 1987, the Montreal Protocol targeted a 50% cut in ODS emissions from developed countries by 1998, using 1992 levels as the baseline. Developing countries were allowed to increase ODS emissions for the first ten years after the Protocol's introduction and then cut emissions by 50% in the following ten years. This gradual reduction, which recognized country-specific needs and global necessities, was well adopted by participants, and targets were met accordingly.

In 2005, the Kyoto Protocol aimed for a 5% reduction in GHG emissions in the first commitment period and an 18% reduction in the second commitment period by all developed countries, while developing countries were not required to make cuts. The Kyoto Protocol again acknowledged the need for economic growth in the developing world with this segregation. However, cuts in GHG emissions affected all sectors of a compliant developed country, leading to greater resistance compared to the Montreal Protocol. Developed countries sought ways to meet their commitments without losing economic growth. Additionally, the heavy burden on developed countries and the authoritative legal obligations resulted in non-participation from major polluters such as the US and Canada.

The developing world was permitted to maintain high levels of emissions. Consequently, under the Kyoto Protocol's emissions trading mechanism, developed countries transferred their most polluting industries to developing nations, particularly China, India, and Brazil. This allowed developed countries to meet their emissions targets while encouraging higher pollution levels in developing countries, potentially increasing global emissions. Such mechanisms led to criticisms of the Kyoto Protocol as being ineffective.
The Paris Agreement was introduced to address these shortcomings, setting a collective goal of limiting global surface temperature increases to 1.5°C. Each country contributes through Nationally Determined Contributions (NDCs), which are regularly updated to ensure the collective target is met. This new framework partially removes the emissions allowances previously granted to developing countries.

The US has played a distinctive role in all three agreements, often perceived as "hostile to international agreements of any variety" (Heath, 2017). In the Montreal Protocol process, despite being a major actor initially, the US showed resistance in 2016 by not ratifying the Kigali Amendment. Regarding the Kyoto Protocol, the US, a significant player in the UNFCCC from 1994, did not ratify Kyoto and was openly opposed to it. The Paris Agreement also saw political contention, with the US leading the agreement under the Obama administration, withdrawing under Trump, and rejoining under Biden. This inconsistency places a heavy burden on other countries, complicating global efforts to combat climate change.

The varying levels of interest in international treaties stem from the different payoff structures each offers. It is argued that the Kyoto Protocol results in few benefits compared to its large costs. This perception does not imply that the entire movement toward climate change mitigation is ineffective, but rather that the Kyoto Protocol itself is seen as insufficient for achieving significant climate mitigation. It remained debatable whether the world will ultimately gain or lose from the Kyoto Protocol.

Full participation of the US in the most parts of Montreal but full rejection of Kyoto, is explained as the result of a simple cost benefit analysis. According to the estimates of the US Environmental Protection Agency, unilateral implementation of Montreal Protocol was expected to cost around 21 billion USD but benefits from the implementation was 1,363 billion USD, most of it coming from the benefits of preventing inclined skin cancer cases. Furthermore, global implementation would increase the benefits by three folds (Sunstein, 2006). So, the country would gain a net benefit from the Montreal even if no other country participated.

On the other hand, the monetized cost the US would pay in participating in Kyoto was much larger than the monetized benefit. Climate change is expected to reduce the US's annual GDP by 100-200 billion USD. Kyoto Protocol is expected to save only 12 billion USD of US's GDP loss through its mitigation processes, further requiring a 325 billion USD upon compliance with its terms and conditions (Sunstein, 2006). This means that Kyoto Protocol does not address climate change properly and its mechanisms should be enhanced. Also, an exceedingly serious problem, putting the US against Kyoto, lies in the fact that the country would have to bear the lion's share of the cost of emissions reductions because the US has been the major emitter during its industrialization period for almost a century.

Pollution can be viewed as an international public good. Since all humans share the same atmosphere, effective climate change mitigation requires universal compliance. Efforts are futile if the US and China, responsible for half of today's GHG emissions, do not participate. They are projected to continue being major emitters in the future. The Kyoto Protocol can be likened to a prisoner's dilemma, where collective compliance with a "binding contract" would yield better outcomes than individual actions. However, for major polluters like the US and China, adhering to a "binding contract" was not advantageous, as it would lead to relatively worse outcomes for them (Sunstein, 2006; Nordhaus, 2020).

On the other hand, agreements that remain purely aspirational, without legal or economic binding, will not achieve targets or sufficiently emphasize the need for action. To make the ideals of the Kyoto Protocol more effective, the international community needs to update or establish a genuine enforcement mechanism for noncompliance. For example, trade barriers could provide both incentives for participating and penalties for not participating. While cutting trade with non-complying countries may harm economies to some extent, a country-specific cost-benefit analysis, considering all factors related to climate change and outlined in the protocol, could determine appropriate sanctions and carbon caps necessary for universal compliance. Since 1990, dynamic optimization models known as "Integrated Assessment Models" have been used to estimate the social impact of carbon emissions, considering factors such as net agricultural productivity, human health, property damage, climate migration, and energy system costs (Newbold et al., 2010; EPA Fact Sheet, 2013). Recently, more studies have focused on the social cost of carbon emissions. The United States Environmental Protection Agency (EPA) has published Social Cost of Carbon (SCC) estimates since 2008. The most recent estimate of the social cost of GHGs indicates that each tonne of GHG emitted costs approximately 36000 to 90000 USD in environmental degradation and negative social impacts (EPA, 2022).

In a cost-benefit approach, the weights of these factors may need to be reconsidered and redistributed. It is essential to recognize that the costs and benefits of climate change mitigation are not solely monetary. The social and psychological impacts related to the environmental crisis, though intangible, may carry significant weight, particularly considering their effects on human health and labor productivity. Studies have shown that temperature increases result in reduced working hours (Rode et al., 2022). It is noteworthy that the lower labor productivity due to high temperatures has both physical and mental health aspects. Future assessment models should consider human psychology in their factor analysis.

We argue that the UNFCCC and the Kyoto Protocol were crucial initial steps toward climate change mitigation. Unlike the Montreal Protocol, which focuses on ozone depletion, the Kyoto Protocol addresses a much broader issue. It successfully acted as a foundational step by drawing global attention to the climate crisis. Despite not achieving universal ratification, the Kyoto Protocol prompted many countries to initiate efforts to reduce GHG emissions. Given the clear anticipated losses from climate change, even non-participating countries have continued to address global warming individually. In the following sections of this study, it is demonstrated that the share of clean energy in total primary energy consumption exhibits a clear trend break around the 2000s for the US and China. Specifically, the US increased its clean energy share from approximately 11% to 19%, and China from 2% to 14% since the 2000s (Figures 2.3.14 and 2.3.15). Additionally, Figure 2.3.16 shows that CO_2 emissions growth in the US has slowed, while China's expanding clean energy sector is expected to lead to lower emissions growth in the future.

We can attribute the failure of Kyoto Protocol both on the ambiguous terms and conditions and also to the resistance of the largest emitters to participate. Thus, in order the climate mitigation efforts following Kyoto Protocol to be successful, either gains from participating or losses from not participating should increase. The Paris Agreement can be perceived as such sort of progress to the Kyoto, trying to correct the mistakes of the Protocol. The required progresses keep occurring with every COP making the climate agreements more inclusive.

2.3. Data and Analysis

The data source for this study is "World Energy Consumption A Database 1820-2020" (Malanima, 2022), published by the Harvard University Joint Center for History of Economics. This extensive database includes a wide range of countries. The complete dataset was obtained from Professor Malanima upon request. The study covers the years 1950 to 2020, encompassing the period just before the advent of nuclear energy and modern renewables. The dataset pertains to energy consumption from primary resources, as defined by Malanima (2022). In the database, primary electricity represents electricity generated solely from renewable resources such as water, wind, geothermal, solar, and modern biofuels. Nuclear energy consumption is reported separately. The energy consumption series are measured in million tonnes of oil equivalent (mtoe).

We first focus on the energy consumption mix. The impact of regional proximity is significant in shaping countries' energy use structures and political behaviors, such as their stance on nuclear energy. Therefore, analyzing the energy mix by regions appears most effective. Another useful approach would be to analyze country groups according to their income levels, given that climate treaties affect high-, middle-, and low-income countries differently. However, considering the country-specific commitments laid out by international treaties, we have decided to analyze the energy mix based on regional proximity. For instance, Annex I countries of the Kyoto Protocol are high-income OECD member countries, primarily located in Western and Eastern Europe, and South America. The US and Canada, which have not ratified the Kyoto Protocol, are in North America.

Figures 2.3.1-2.3.8 depicting regional energy mixes indicate that clean energy became prominent in most regions after the 1970s. Europe, North America, and Latin America increased their clean energy consumption sharply, following the OPEC oil crisis. In contrast, Oceania, the Middle East, Africa, and Asia did not respond similarly to the OPEC crisis. This difference is understandable when comparing the total energy consumption of Europe and North America to other regions; Europe and North America's consumption is three times higher. The significant energy demands in Europe and North America drove these countries to seek alternative energy sources as energy prices soared post-OPEC crisis.

During this period, Europe and North America increased their nuclear energy consumption, while Latin America focused on renewable energy. Latin America sought alternative resources but did not opt for nuclear energy, finding a mild transition to renewables sufficient for their energy needs. However, the rapidly growing regions of North America and Europe could only meet their energy demands through nuclear energy, which was more reliable and provided a higher energy supply compared to renewable energy at that time.

The energy transition and reluctance towards nuclear energy exhibit distinct behaviors across regions. Latin America and Oceania have shown a preference against nuclear energy all along, while the 2010s marked a negative turning point in nuclear energy consumption for many parts of the world. Notably, Western Europe and Asia experienced a slowdown in nuclear energy consumption post-2010s, largely due to the aftermath of the Fukushima Nuclear disaster in 2011. This slowdown has led to renewable energy becoming the primary clean energy resource, overtaking nuclear

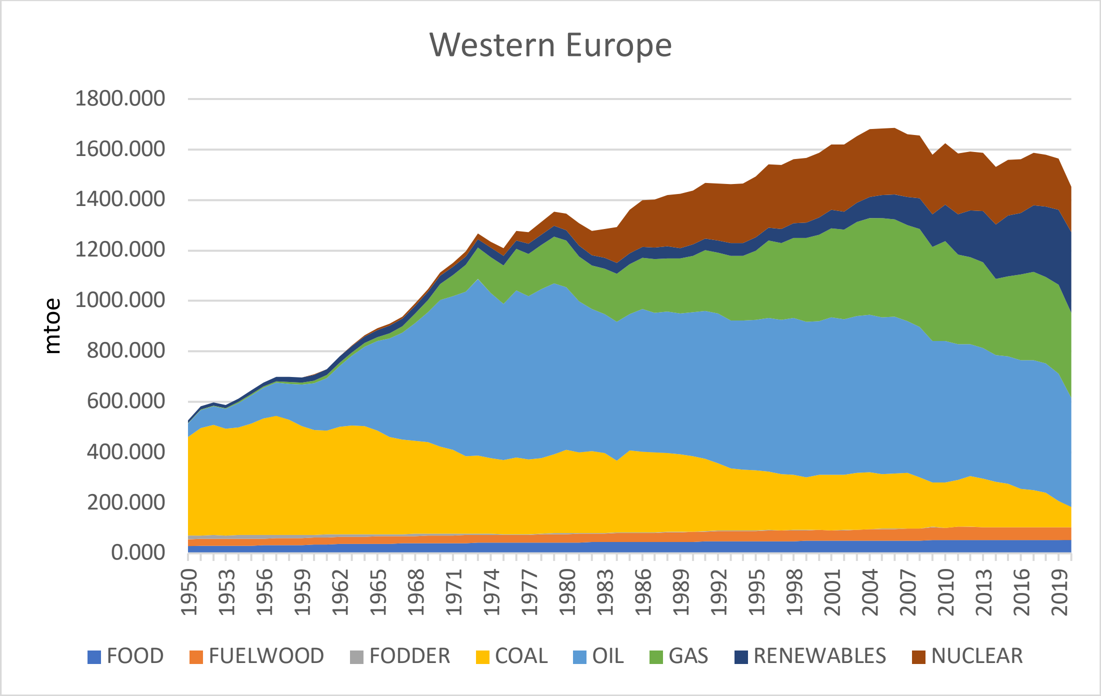

Figure 2.3.1 Energy Consumption Mix of Western Europe

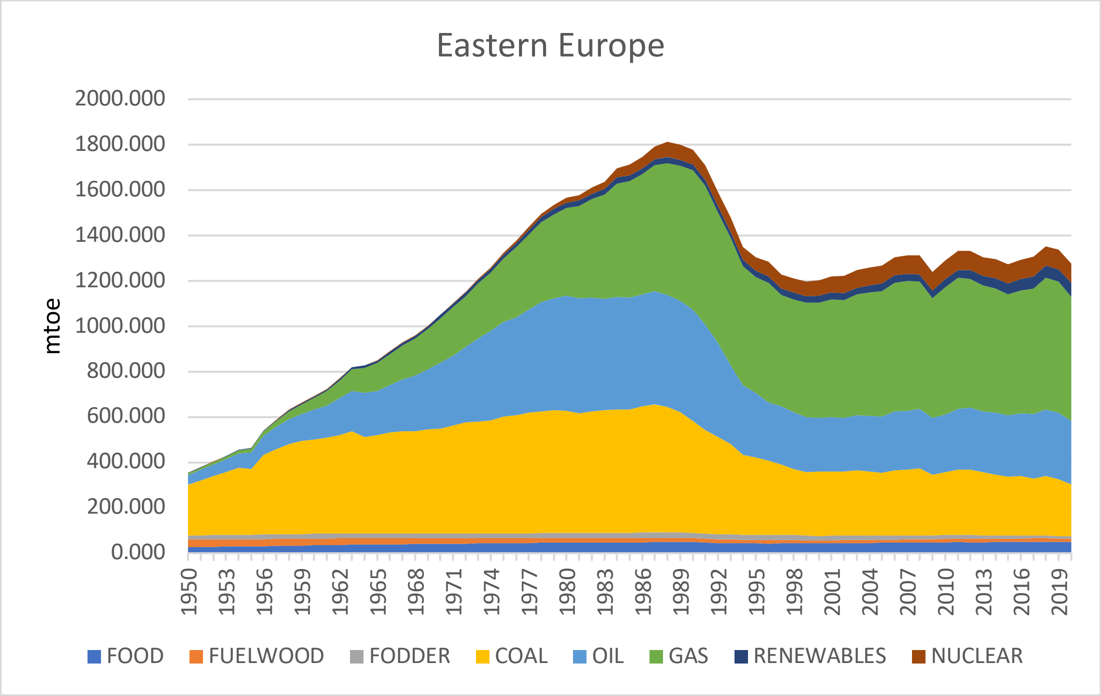

Figure 2.3.2 Energy Consumption Mix of Eastern Europe

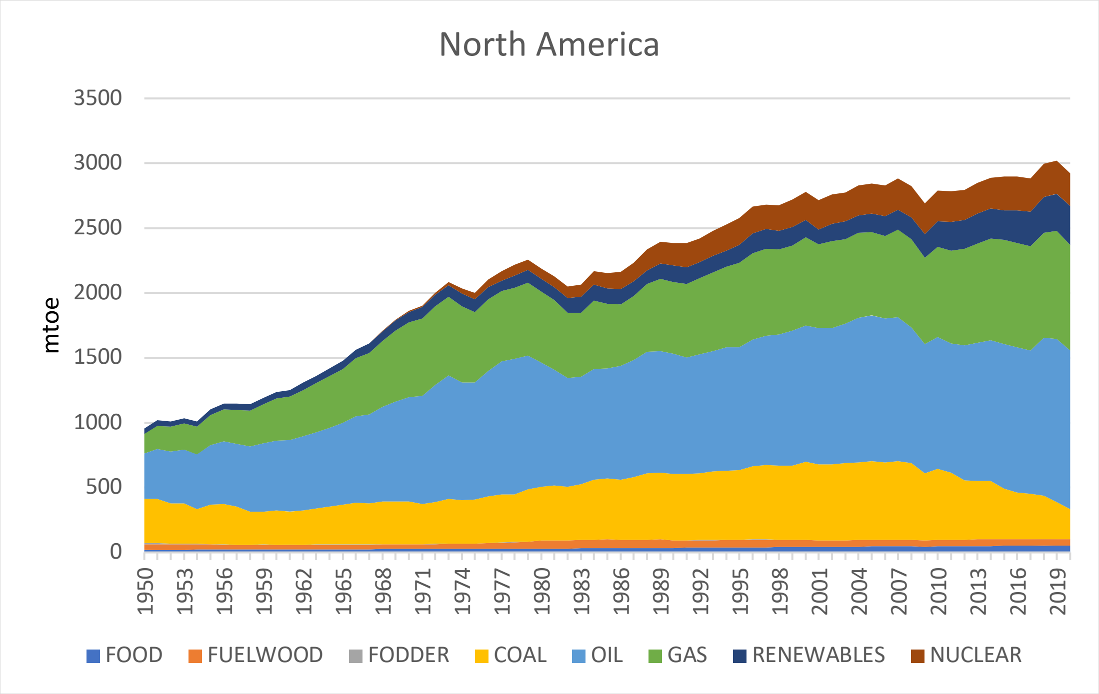

Figure 2.3.3 Energy Consumption Mix of North America

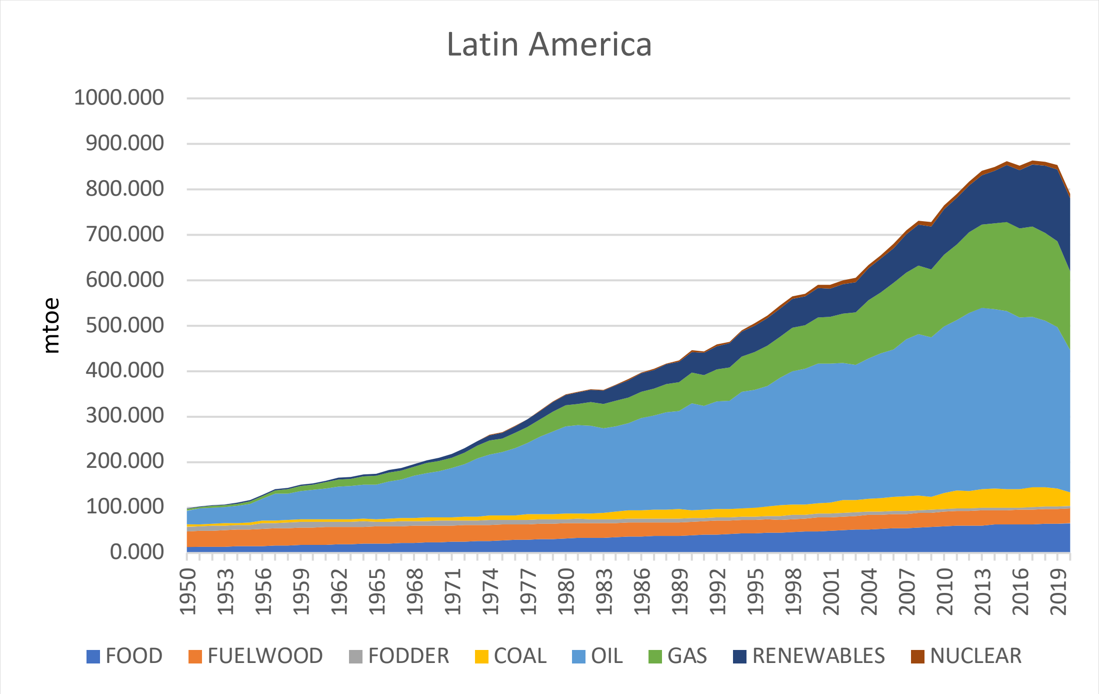

Figure 2.3.4 Energy Consumption Mix of Latin America

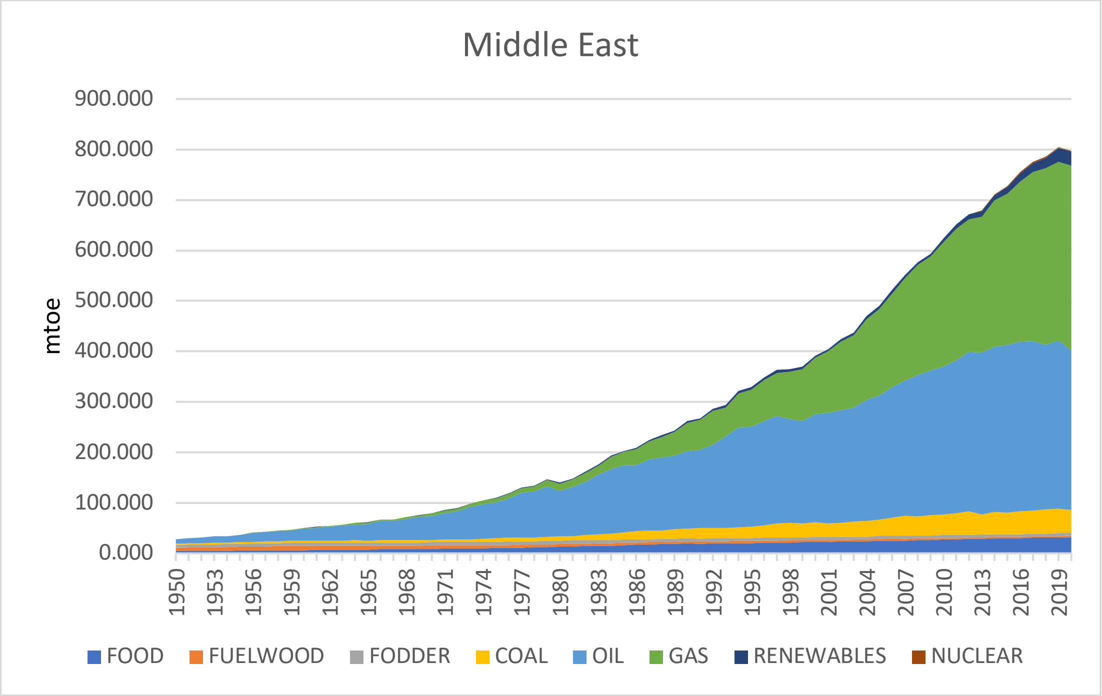

Figure 2.3.5 Energy Consumption Mix of Middle East

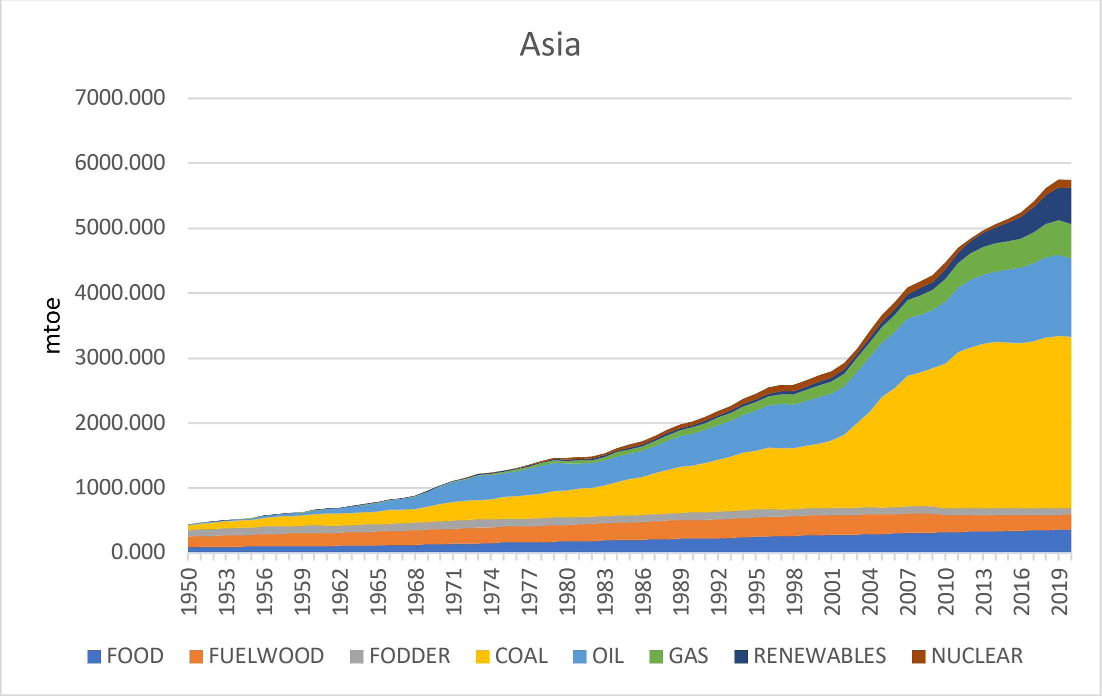

Figure 2.3.6 Energy Consumption Mix of Asia

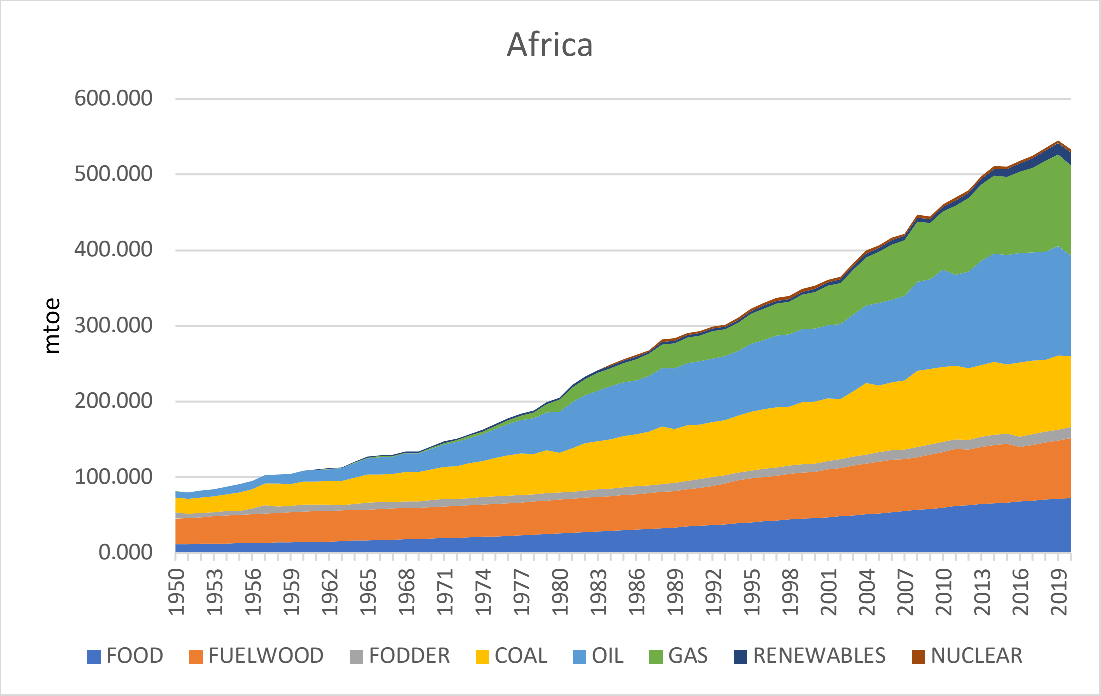

Figure 2.3.7 Energy Consumption Mix of Africa

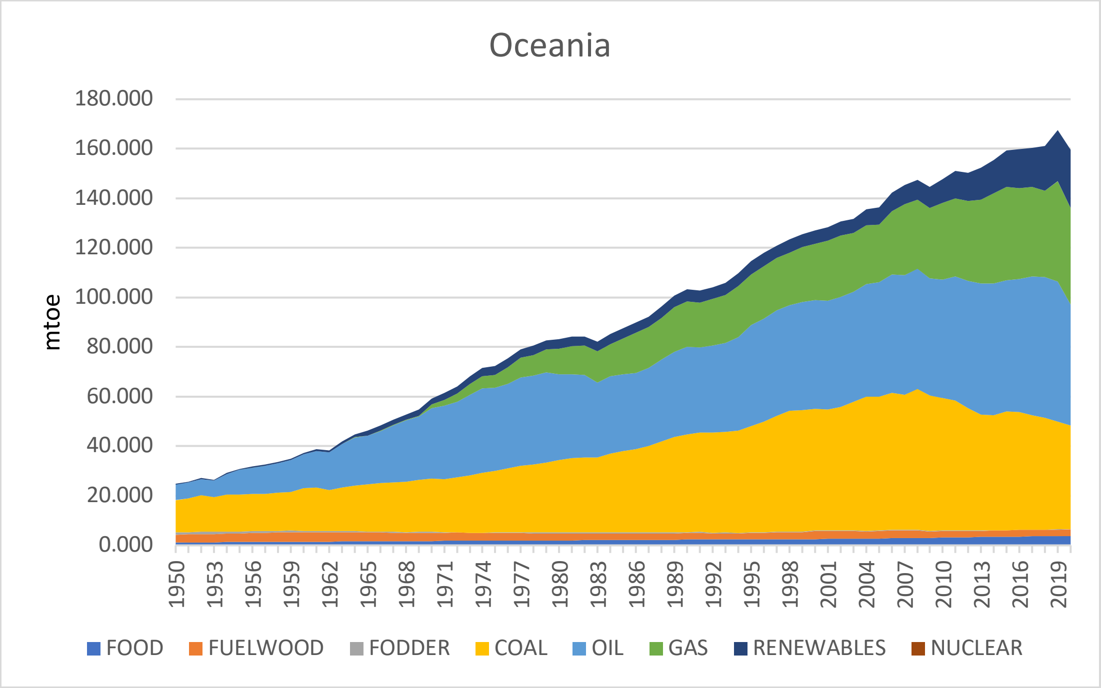

Figure 2.3.8 Energy Consumption Mix of Oceania

energy. Eastern Europe, influenced by Russia's nuclear ambitions, maintains a higher share of nuclear energy, with Russia supplying 21% of its electricity consumption from nuclear power (Korobeinikov, 2021).

Until the last two decades clean energy sources, renewables, and nuclear energy, did not have much space in the aggregate energy mix of Middle East, Asia and Africa. Renewable energy had a tiny share for Eastern Europe, Middle East, Asia and Africa, which has become visible only after 2000s, with the progress starting with Kyoto Protocol.

The small amounts of clean energy consumption in Eastern Europe, Asia, and Africa until recent years can be attributed to lower technology investments linked to low economic development, as renewable energy and nuclear energy facilities involve high-tech processes. Conversely, the low amounts of clean energy consumption in the Middle East can be attributed to resource management, given the region's abundance in fossil fuel resources, resulting in less focus on clean energy. Europe, America, and Oceania halted the rapid growth of fossil fuel consumption by investing in energy-efficient production processes and clean energy technologies. However, the Middle East, Asia, and Africa continued to increase fossil fuel consumption, reflecting the different approaches towards developed and developing countries by the UNFCCC and the Kyoto Protocol.

Besides the environmental goals of reducing energy consumption, other factors such as significant economic and geopolitical events have contributed to an apparent decrease in energy consumption. In 1990, Eastern Europe experienced a significant decline in energy consumption due to the dismantling of the Union of Soviet Socialist Republics (USSR). Similarly, global energy consumption declined during the 2008 economic crisis and again in 2020 following the Covid-19 pandemic. Declines in coal consumption are observed in Europe, North America, and Oceania, contrasting with Asia and Africa. Despite these shifts, oil and natural gas remain the primary energy providers worldwide.

Some of these events can be treated as exogeneous, however, each country has its own response towards individual events aside from the regional group it belongs. Country-specific studies in energy economics are necessary because a universal policy may not be effective; each country has a unique energy transition path.

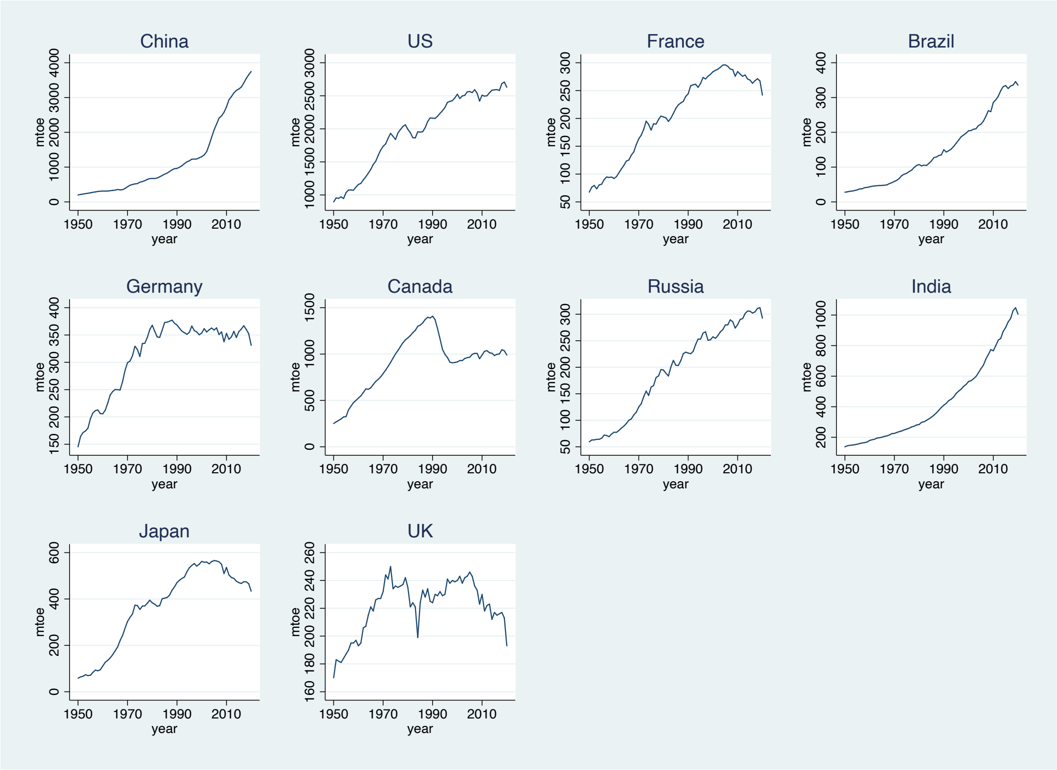

Figure 2.3.9 Total Primary Energy Consumption

Country-specific policies prior to these events or resulting governmental or social reactions will endorse country-specific structural changes inside each economic system. Also, the Kyoto Protocol and the Paris Agreement set country-specific targets for lowering GHG emissions. Even the preference of the replacement energy source against fossil fuels is country-specific as some countries prefer nuclear energy while others rely on renewables. That is why this study focuses on country-level analysis, targeting the top 10 countries with the highest clean energy consumption as of 2020. These countries, including China, the United States, France, Brazil, Germany, Russia, Canada, India, Japan, and the United Kingdom, drive the clean energy sector. Examining their responses to major events is significant.

Figure 2.3.9 illustrates the series of total primary energy consumption. Until the 2000s, most countries showed predominantly positive trends in primary energy consumption. A decline is observed in the early 1980s for the US, France, Germany, Japan, and the UK, coinciding with the oil glut following the 1970s oil crisis. A decrease in energy consumption in Russia around 1990 aligns with the dismantling of the USSR. The 2008 Global Economic Crisis caused a small decline followed by a recovery in energy consumption for almost all countries. The end of each country's series, except China, reveals a decline in energy consumption in 2020 due to the COVID-19 pandemic.

Recently, there has been a notable decrease in energy consumption growth among these countries, influenced by environmental concerns and the global energy efficiency movement. However, China, Brazil, and India continue to experience growth in energy consumption. These developing nations were exempt from the more stringent terms of the Kyoto Protocol. Reducing energy consumption is foundational in environmental policies aimed at achieving lower greenhouse gas (GHG) emissions. Countries must promote clean energy consumption to expedite the decline in GHG emissions and address environmental challenges effectively.

Figure 2.3.10 illustrates the sectoral dominance of the United States over the years and the subsequent rise of China, which has recently surpassed the US in clean energy consumption. The clean energy consumption levels of other countries in the list remain comparatively lower than those of China and the US. It is important to note that the data presented in Figure 2.3.10 accounts for aggregate clean energy consumption for each country, without considering per capita consumption. This distinction is crucial as it acknowledges the significant contributions of China and the United States to the clean energy sector, reflecting their substantial overall consumption levels.

Our analysis indicates that the series of renewable and nuclear energy consumption underwent various major shocks during this period. The first shock occurred during the 1970s oil crisis, the second during the Three Mile Island Accident in 1979, the third during the Chernobyl disaster in 1986, the fourth during the implementation and aftermath of the Kyoto Protocol in the 2000s, the fifth following the Paris Agreement in 2015, and the sixth following the Fukushima Nuclear Disaster in 2011. These events likely influenced countries to increase their clean energy consumption in response to the oil crisis, the Kyoto Protocol, and the Paris Agreement, while subsequently witnessing a decline in nuclear energy consumption levels due to security concerns following the Three Mile Island, Chernobyl, and Fukushima incidents.

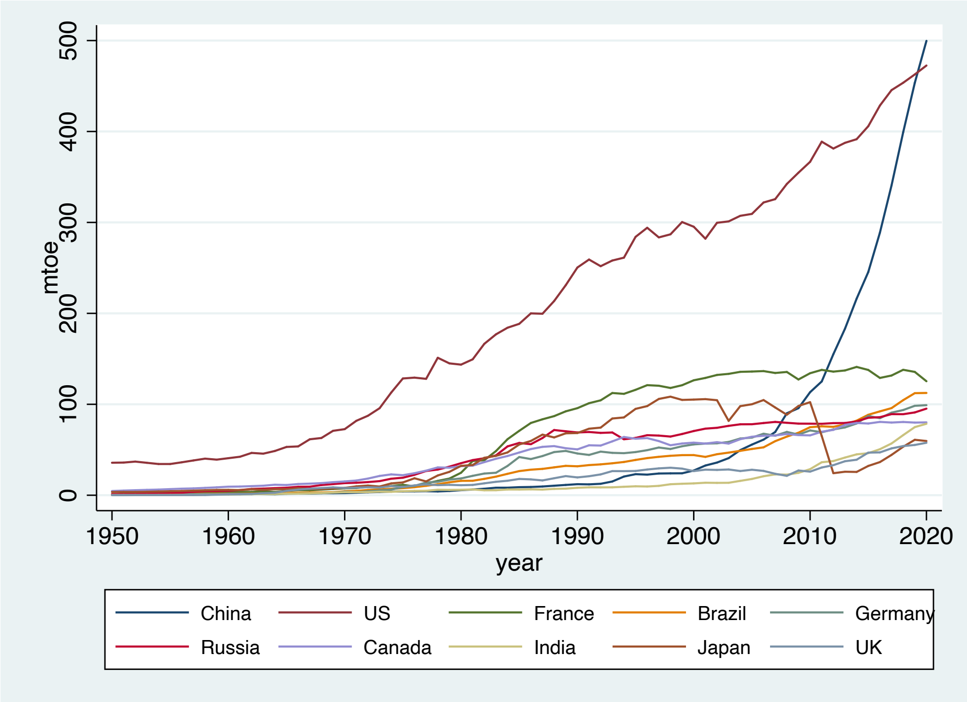

Figure 2.3.10 Clean Energy Consumption

Examining the timeline from 1950 to 2020, we observe an overall positive trend shift in clean energy consumption following the oil crisis of the 1970s. China experienced a remarkable surge in clean energy consumption during the 2000s, while Japan faced a decline following the Fukushima Nuclear Disaster in 2011. These events highlight the dynamic changes that have shaped the clean energy landscape.

Clean energy, comprising both renewables and nuclear energy, serves as the focus of this study. However, we have chosen to analyze renewables and nuclear energy separately due to the observation that these two sources respond differently to various historical events. This differentiation allows for a more nuanced understanding of the dynamics and patterns exhibited by each energy source. By examining renewables and nuclear energy independently, we can gain deeper insights into their individual trajectories and the factors influencing their adoption and development.

Nuclear accidents such as the Fukushima Disaster had contrasting effects on renewable and nuclear energy consumption. If we were to use aggregate clean energy consumption as the sole variable of analysis, we would not be able to accurately observe the true impact of such events. The opposing directions of change in renewables and nuclear energy consumption would cancel each other out in the aggregate data, leading to an inaccurate representation of the overall dynamics.

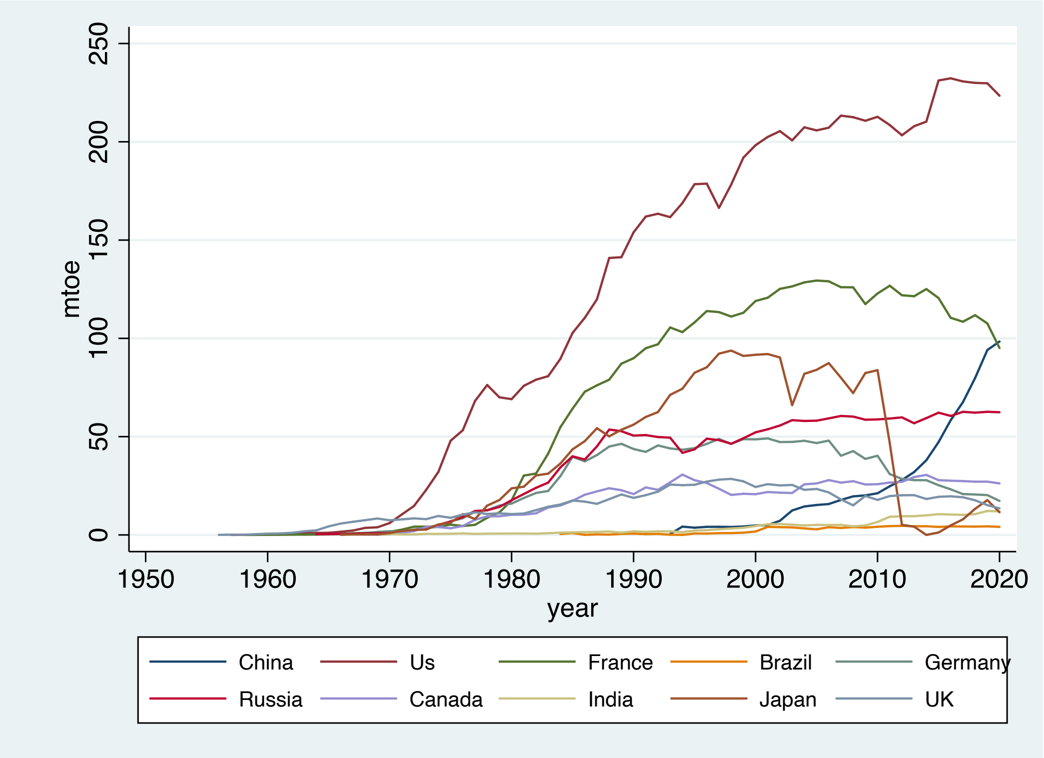

Figure 2.3.11 Nuclear Energy Consumption

Another crucial observation is that the renewable and nuclear energy series follow distinct paths for each country. This implies that country-specific factors play a significant role in shaping their energy choices and consumption patterns. For instance, in the aftermath of the 1970s' oil crisis, while many countries leaned towards nuclear energy, Brazil opted to replace oil with renewables. Therefore, relying solely on aggregate clean energy consumption would not provide reliable insights into the country-specific changes and variations in energy sources.

By analyzing renewables and nuclear energy separately, we can capture the nuanced dynamics and country-specific responses to different events, enabling a more comprehensive understanding of the factors influencing energy choices and consumption patterns. In this regard, Figures 2.3.11 and 2.3.12 indeed provide valuable insights into the dynamics of renewable and nuclear energy consumption.

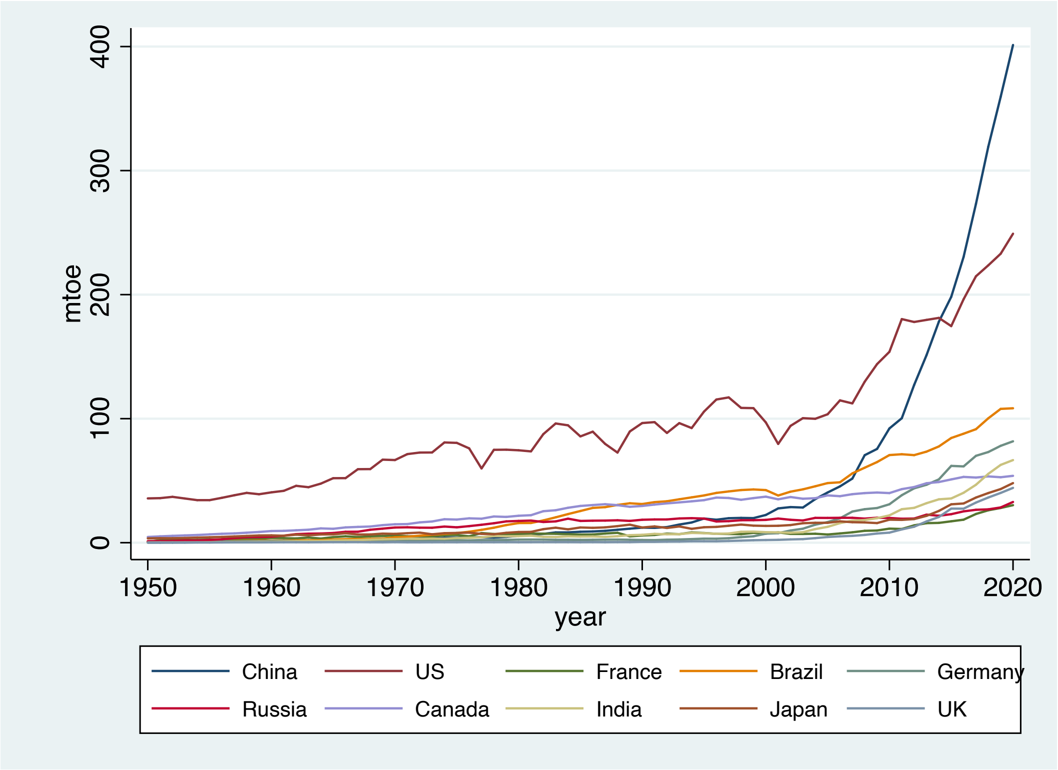

Figure 2.3.12 Renewable Energy Consumption

These figures enable clear observation of the immediate increase in nuclear energy consumption during the 1970s, while renewable energy consumption remained relatively low until the 2000s. The figures also facilitate easy comparisons between countries, with the United States and France consistently occupying the top positions in nuclear energy consumption, while China and the United States rank first and second in renewable energy consumption.

It is noteworthy that China has shown a strong focus on both clean energy sources since the 2000s, but with a greater emphasis on renewable energy, rather than nuclear energy. This emphasis is evident in the figures as renewable consumption reaches 400 mtoe and nuclear energy remains at 100 mtoe.

Moreover, Figures 2.3.11 and 2.3.12 reveal that the decline observed in 2011 pertains specifically to nuclear energy consumption for Japan, decreasing from around 80 mtoes to almost 0, which is a direct response to the Fukushima Disaster. Germany also appears to have responded to Fukushima with an immediate 20% reduction of its reliance on nuclear energy. Notably, even though nuclear energy had the highest share in total energy consumption for two decades, France has also gradually begun to lower its nuclear energy consumption after the Fukushima incident. The stagnation in nuclear energy consumption in France started around the 2000s.

Figure 2.3.13 presents the combined view of renewable energy consumption and nuclear energy consumption for each country, providing a convenient platform for country-specific comparisons. Consistent with our earlier claims, most countries increased either renewable or nuclear energy consumption in response to the 1970s oil crisis. During the period of the Kyoto Protocol (1997-2005), the growth of renewable energy accelerated. It is notable that around the time of the Kyoto Protocol, many countries displayed reluctance to expand their nuclear energy production. This hesitance can be attributed to two significant nuclear accidents in the 20th century: the Three Mile Island Accident in 1979 and the Chernobyl Accident in 1986.

A remarkable observation is that, except for China, all the countries in this group have experienced a decline or slowdown in nuclear energy consumption in the 21st century. Among the 10 countries analyzed, France, Brazil, Germany, Japan, and the UK are particularly noteworthy as they have actively reduced their reliance on nuclear energy following the Fukushima Disaster in 2011. Germany, in fact, has made the decision to completely phase out nuclear energy by 2022, with the date of implementation being April 16, 2023, albeit slightly prolonged due to the natural gas shortage following the Russian invasion of Ukraine in 2022.

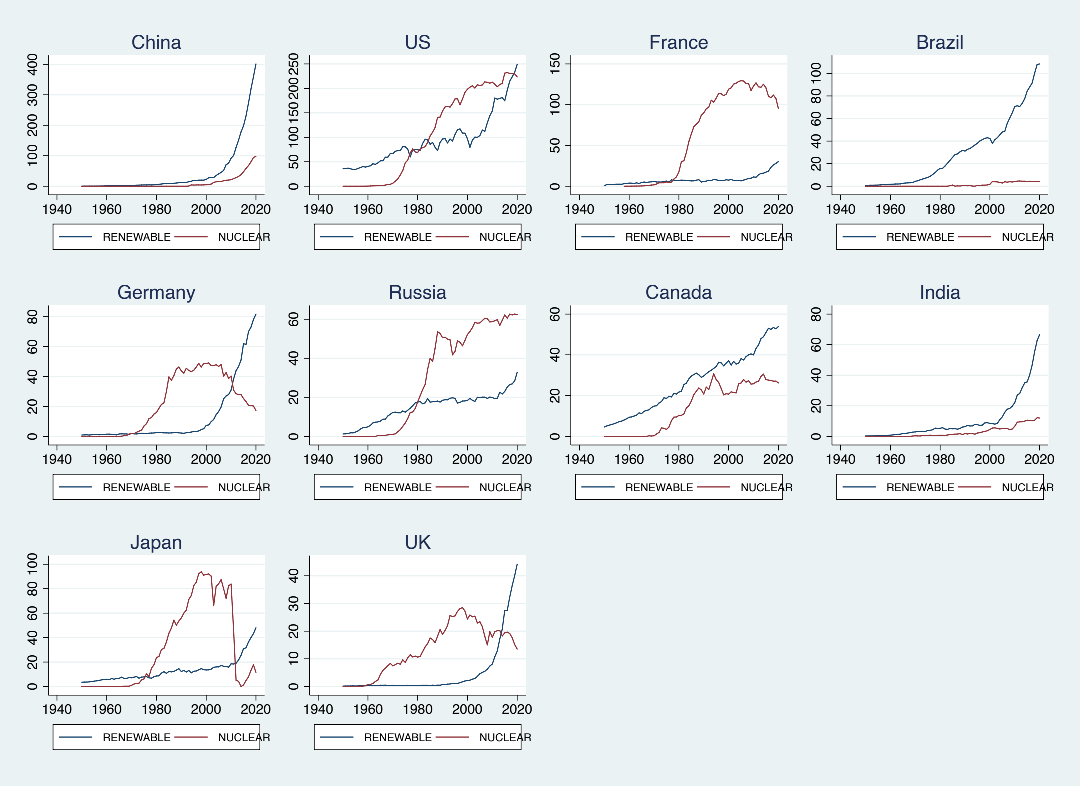

Figure 2.3.13 Renewable Energy and Nuclear Energy Consumption Levels (mtoe)

It is important to recognize that nuclear energy has both environmental benefits, as it provides GHG-free electricity, and environmental challenges, particularly in managing nuclear waste and the existing risk factors from possible accidents. The decision regarding nuclear energy involves careful considerations and trade-offs. Nuclear energy should be a part of the clean energy programs along with renewables if reliance on green energy is the goal. This is because governments can only prevent energy blackouts in their energy transition process with a firm clean energy supply which can be provided only by utilizing every possible clean energy resource. Also, nuclear energy is known for its consistent energy provision, unlike renewable energy.

In fact, nuclear energy may be the inevitable solution to climate change as the only nations who have reached their first commitment period targets to the Kyoto Protocol even before the period started were France and Sweden with their strong nuclear energy sector.

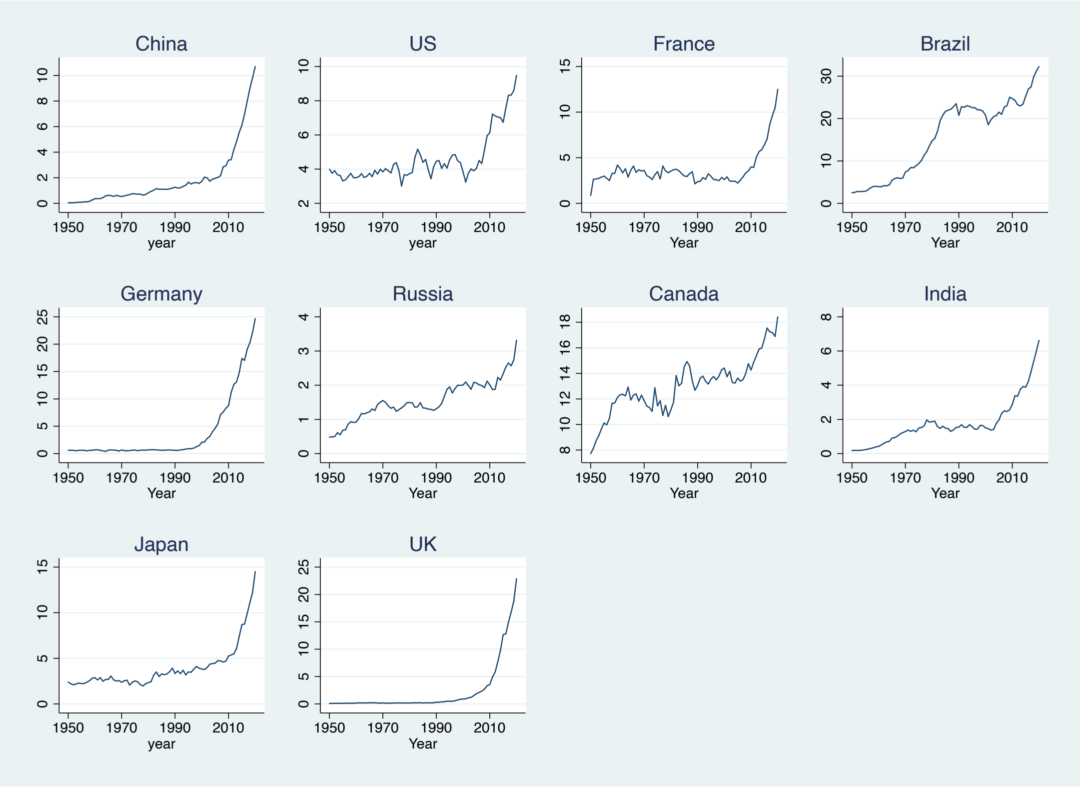

Figure 2.3.14 Share of Renewables in Primary Energy Consumption (%)

The world is moving towards cleaner energy every day. Even the Middle Eastern governments have investments in solar panel building projects inside borders aside from the fact that there is overwhelming interest in the financing of clean energy by the Middle Eastern companies out of borders. Also, we can infer that despite all the hesitation against nuclear power, we cannot unsee the developments in the sector. For instance, building of small modular reactors has been accelerating recently, especially in the US. However, there are some bottlenecks against realizing clean energy projects. One of the complaints is the long waiting periods that are required to acquire construction permits from government bodies. There is also a concern for the short supply of critical minerals used in clean energy technology, such as lithium for the production of solar panels and EV batteries, and uranium for nuclear reactors.

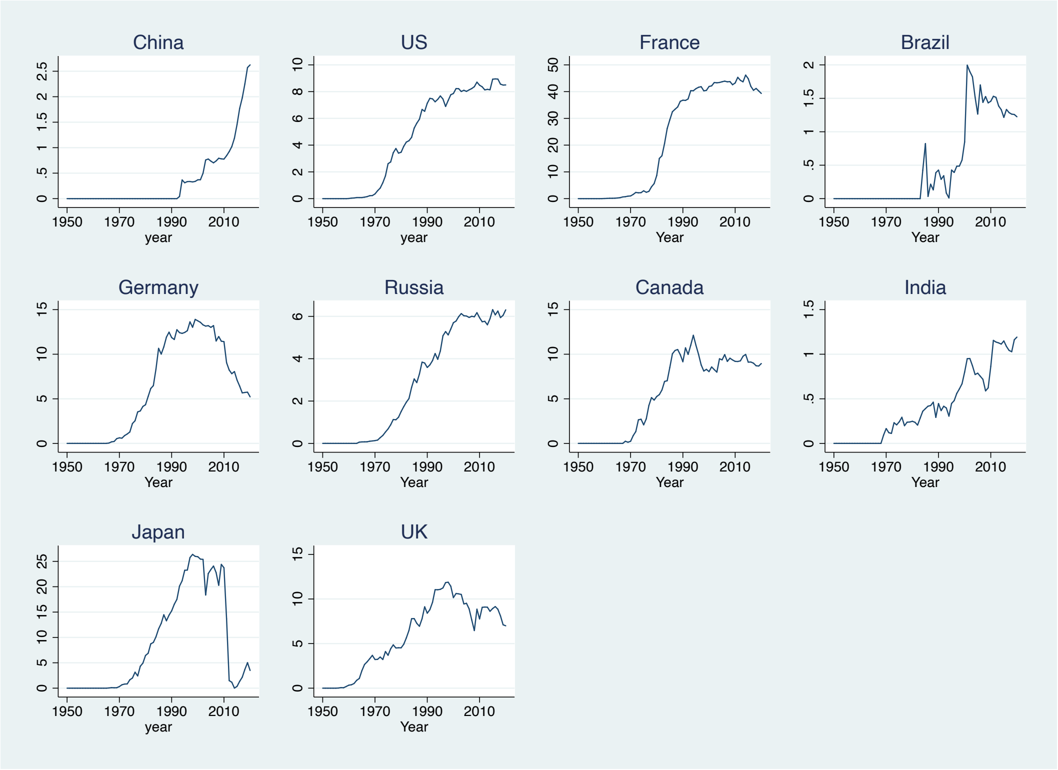

Figure 2.3.15 Share of Nuclear Energy in Primary Energy Consumption (%)

The variables of interest in the following graphs in Figures 2.3.14 and 2.3.15 are the share of renewables in primary energy consumption and the share of nuclear energy in primary energy consumption. The focus on the share series is motivated by the aim to assess progress towards a carbon-free world. The pursuit of an environmentally sustainable energy sector involves reducing overall energy consumption from any source and optimizing resource utilization. Merely relying on coal, oil, and natural gas does not represent the most efficient use of resources as they lack viable replacements. To save the environment and promote energy efficiency, it is essential to decrease total energy consumption as the economy grows while increasing the use of alternative, non-carbon-emitting resources. Therefore, analyzing the shares of clean resources in total energy consumption provides the most meaningful perspective from an environmentally conscious standpoint.

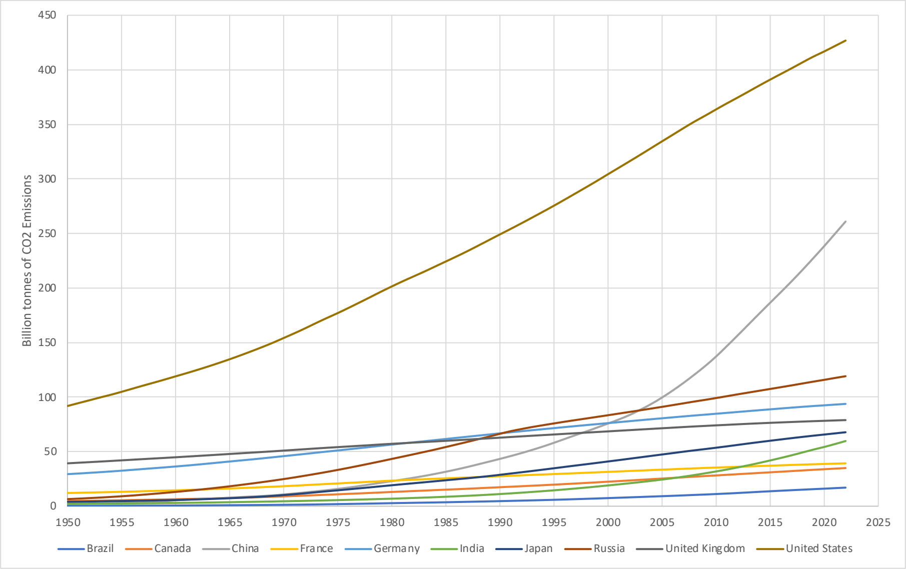

Figure 2.3.16 Cumulative CO2 emissions by major clean energy consumers.

Source: Global Carbon Budget (2023) – with major processing by Our World in Data

Renewable energy has gained popularity over the past two decades, with significant growth observed during this period. Prior to that, renewable energy consumption was relatively low. On the other hand, nuclear energy has been preferred by most countries since the 1970s. However, some countries have started decreasing their reliance on nuclear energy, while others have slowed down their growth in recent years. The decline in nuclear consumption is primarily attributed to nuclear accidents, which have raised safety concerns. As a result, countries that consider nuclear energy unsafe have shifted their focus towards renewable energy, leading to an increase in the share of renewables. It is worth noting that this is one of the reasons why the Kyoto Protocol is considered a structural change especially for renewable energy but not for nuclear energy. We can observe that Germany, Brazil and the UK are major investors in renewable energy. Brazil even showcases a renewable energy success story as the country has already met its NDCs for 2°C target of the Paris Agreement by investing in renewables (Black et al., 2023).

Efforts toward climate change mitigation are evident in the figures of clean energy consumption. However, when examining the primary objective of these efforts—reducing carbon emissions—the results are less encouraging. Figure 2.3.16 shows that carbon emissions continue to rise. An optimistic view suggests that without these efforts, the increase would have been much faster. For instance, without international compliance, emissions in the EU would have increased by 12-50% by 2010, and Japan’s emissions would have risen by 20-33%. With the commitments of the "flawed" Kyoto Protocol, EU emissions have declined by 10%, and Japan’s emissions have increased only by 6% (Grubb, 2016). This indicates a modest deceleration in the growth rate of emissions for developed countries. However, for developing countries like China and India, the rate of increase in emissions is accelerating.

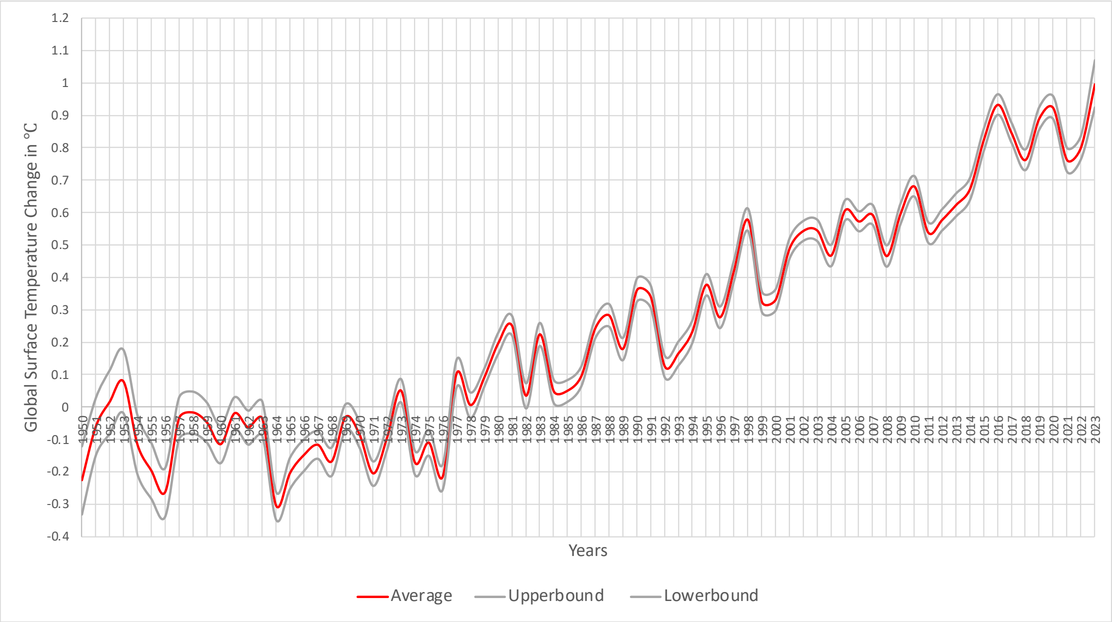

Figure 2.3.17 Global Surface Temperature Anomalies since 1950

Source: Met Office Hadley Centre (2023) – processed by Our World in Data

Figure 2.3.17 shows that global surface temperatures have been rising since around the 1970s. The rise has been somewhat slower since the 2000s, but the slowdown does not seem significant. It is still too early to make conclusions about the aftermath of the Paris Agreement. However, we can claim that international efforts to reduce global surface temperatures remain limited.

There is ongoing research on the timing of the peak year of GHG emissions. For reaching the 1.5°C target at the end of this century, according to the estimations of the Intergovernmental Panel for Climate Change (IPCC), the peak year should be 2025 (Fyson C. et al., 2023). Maybe a more important question than the timing of the peak year is how fast a decline in emissions following the peak year is required for achieving 1.5°C. It is clear that we need much faster development and diffusion of Low Carbon technologies, such as electric vehicles, heat pumps and green steel backed by the Carbon Dioxide Removal technologies such as afforestation, soil carbon sequestration and others (Terlouw, Tom, et al., 2021).

Fossil fuels dominate the world's energy supply because in the past they were cheaper than all other sources of energy. If we want the world to be powered by safer and cleaner alternatives, we have to make sure that those alternatives are cheaper than fossil fuels. In recent years renewables realized this desired price improvement (Max Roser, 2020). Figure 2.3.18 shows the Levelized Costs of Energy (LCOE) from various energy sources. LCOE represents the per-unit cost (typically per megawatt-hour) of building a power plant from the desired resource as well as the ongoing costs for fuel and operating the plant over its lifetime. In 2009 the cheapest energy sources were gas, wind, geothermal and coal. It was much cheaper to build a new power plant that burns fossil fuels than to build a new solar plant.

Renewable energy technologies are an example of learning by doing. As they are produced more, their technology gets cheaper. Since the energy source is unlimited (sun and wind) just by means of technological developments one can produce cheaper and higher amounts of energy every consecutive year. Solar energy was a rare technology as it was only used to supply electricity for satellites, in 1958. Even if the prices were high, there was a small but fixed demand for this high-tech application. Then, the first territorial applications were in 1970s in remote locations such as lighthouses and remote railroads where connection to grid was costly. As the application areas grew and with the international and regional support from governments through climate mitigation process, prices fell rapidly. Renewable Technologies are examples of Wright's law stated by Theodore Paul Wright in 1936, where each doubling in experience leads to the same relative decline in prices, similar to the historical development of computational and AI Technologies (Max Roser, 2020).

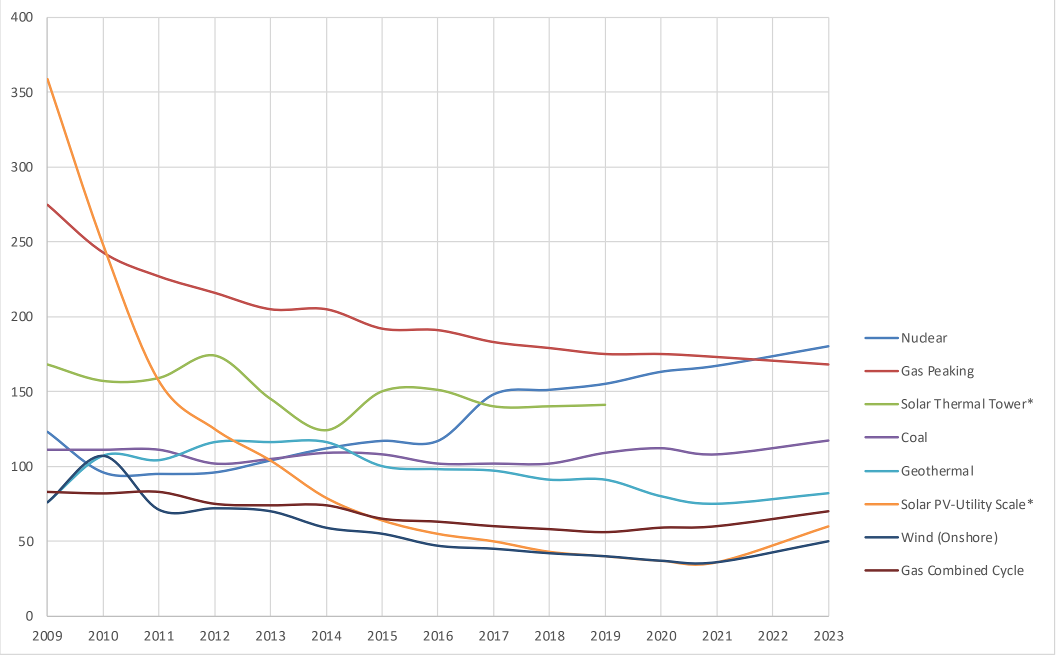

Figure 2.3.18 Mean unsubsidized global levelized cost of energy (LCOE) by source: USD per megawatt-hour

Source: Lazard Capital (2023)

The reason why fossil fuel and nuclear technologies do not show a similar learning experience is that the price of energy from these resources is determined by the cost of the used fuel itself. Also, particularly for nuclear energy, the technology is not standardized as it is seen as a private technology to some extent, where the owner states have the liability of knowledge. On the contrary, when a standard technology is applied more it is deemed to improve more as in the case of renewables.

The main reason for the rising prices of nuclear energy is increased regulation for higher safety. Even if nuclear energy is not so attractive as the prices are not decreasing, it could still become more important in the future because it can complement the weaknesses of renewables such as intermittency of electricity from renewables and the larger land use of renewable power facilities (Max Roser, 2020). Soaring input costs, shipping problems and the energy crisis following Russia's invasion of Ukraine pushed up the price of clean energy equipment in 2021 and 2022, which is visible in Figure 2.3.18. Demand for this equipment skyrocketed as the clean energy transition gained pace in many markets. The challenges eased in the first half of 2023 and prices were lowered to 2019 levels recently (IEA, 2023).

Clean energy, comprising both renewables and nuclear energy, is set to become the primary energy source of the future. The growing energy demand will predominantly come from developing and underdeveloped countries. As clean technologies become more affordable, this new demand can be met with low-carbon resources, offering a solution to global warming. Supplying energy at lower prices also translates to higher real incomes, addressing the need for economic growth in the developing world. Consequently, clean energy may be the key solution to both environmental degradation and economic development (Max Roser, 2020).

2.4. Conclusion

While efforts following the UNFCCC since 1992 led to some reductions in emissions, the necessary "dramatic cuts" have not been realized. The ambiguity surrounding the Kyoto Protocol and the Paris Agreement persists. The Kyoto Protocol attempted to establish a market structure for carbon emissions, where each country had a limited emissions account and could trade emissions within these limits. However, its voluntary structure allowed for unrestrained withdrawals and free-riding. Kyoto Protocol’s failure was succeeded by the Paris Agreement, which adopts both a top-down and bottom-up approach with the universal 2°C goal and the NDCs. The US withdrawal undermined the consistency of this approach, making the dual strategy unfeasible. Again, the uncoordinated and voluntary nature of the Agreement led to its failure (Nordhaus, 2020). The latest progress in international efforts initiated by the UNFCCC is COP28, held i in November 2023. Despite high expectations for the summit, defined as a potential breakthrough by many representatives, the outcomes did not meet these expectations.

Addressing climate and energy regulations requires government or international non-profit interventions, as the free market alone will not prioritize climate protection unless it becomes integral to economic growth processes. Emission permits integrate climate concerns into both firm-level and government-level optimization problems. However, determining the permitted emissions level to keep global temperature rises below 1.5°C is challenging. Issuing too many permits undermines emissions targets, while too few permits restrict industrial production and supply. This dilemma applies to other regulations like carbon taxes and clean energy subsidies, necessitating a scientific focus.

Governments and intergovernmental organizations must identify optimal energy uses and climate policies to address the long-term impacts of climate change. However, political cycles often constrain individual governments, as leaders prioritize short-term election timelines over long-term climate issues. Consequently, climate policies that could slow production and economic growth are often unpopular during election periods. Thus, addressing climate change requires a dedicated focus at the state level under an independent organization, free from governmental changes.

Quantifying the gaps in emission targets is one challenge, but political will is another. Progress has been made since the Paris Agreement in 2015, with increased ambition and more effective NDCs. Investment in climate change mitigation needs to grow significantly, with global energy investment needing to increase six-fold by 2030 (Black et al., 2023). For clean energy to be preferred over conventional energy, it must be cheaper. The costs of solar panels, wind turbines, clean energy storage technologies, and EVs need to fall, driven by technological advancements. Figure 2.3.18 shows that the decline in renewable energy costs continues, with the Levelized Cost of Energy for solar PV and onshore wind reaching historic lows since 2010, making these technologies the cheapest energy sources since 2015. However, concerns about storage costs remain (Lazard, 2023).

The cost of inaction on climate change is expected to exceed the cost of preventive investments. Research suggests that failing to mitigate climate change could reduce GDP by 1-2% in developed countries and by 5% in developing countries (Sunstein, 2006). Achieving climate targets at the macro level will enhance energy efficiency and local clean energy production, reducing industrial energy costs. Additionally, health costs from climate-related diseases and damage from natural disasters will decrease.
Governments should focus on eliminating carbon-emitting technologies and phasing out fossil fuels across all sectors to achieve significant emissions reductions (Climate Action Tracker, 2023). Countries fear falling behind in the economic race if they pursue deep emissions cuts. However, even rapidly developing countries like China and India have committed to substantial climate targets under the Paris Agreement. They may now compete in the clean energy sector, transforming this "hurdle" into an opportunity (Sunstein, 2006).

The debate on the ineffectiveness of international agreements due to their non-binding and voluntary nature has spurred innovative approaches. Carbon taxes are considered the most popular policy tool for combating climate change. However, a comprehensive portfolio of policies is needed for individual countries to achieve effective results unilaterally. Binding trade measures that create a feedback mechanism have proven effective, promoting a multilateral process. As seen with the Montreal Protocol's targets on hydrofluorocarbons, a binding agreement on GHG emissions targets, imposing penalties like trade barriers on non-compliant countries, is necessary. Such a framework could resemble Nordhaus's Climate Club. Climate change mitigation requires participation from all countries, especially from major emitters like China and the US. In a Climate Club, the incentives for membership should outweigh the costs of compliance, ensuring no member wants to leave. Nordhaus (2020) suggests that a carbon pricing mechanism (dollars per tonne of carbon emitted) would be more effective than emission limits (tonnes), providing a standardized measure with an annually increasing global carbon price. Additionally, non-participation should incur penalties, such as uniform tariffs on imports to member countries. The Club could set country-specific commitments depending on the development level, similar to the differentiated commitments in the Montreal and Kyoto Protocols.

Complementary agreements, such as setting minimum carbon prices within the Paris Agreement’s flexibility mechanisms, are needed to make emission reductions financially valuable. However, despite China's significant investments in clean energy sectors, its carbon prices remain low due to the strong influence of the coal and fossil fuel industries.

As global attention on climate change intensifies, new investment and financial mechanisms emerge. Using SDRs (Special Drawing Rights) under the IMF’s Resilience and Sustainability Trust (RST) to fund climate mitigation projects is considered revolutionary for the climate cause (Chmielewska and Sławiński, 2021). SDRs, created in 1969 to supplement IMF member countries' official reserves, provide affordable long-term finance. Defined by a basket of major currencies (US dollar, Euro, Chinese Yuan, Japanese Yen, British Pound), SDRs facilitate financial liquidity. These mechanisms simplify the design of national climate policies. The Paris Agreement may have triggered these developments, fostering a structural change in how countries and intergovernmental entities perceive the clean development industry - not just as burden-sharing but as a new growth area. With government support for renewable energy, tax subsidies for renewable electricity, and high carbon pricing on fossil fuels, the cost of renewable energy has become much lower than conventional energy.

The literature and international treaties emphasize the need for innovative and effective ways to support clean energy. However, skepticism remains about the clean energy sector's overall impact on reducing emissions. Questions arise, such as whether the production of solar panels and wind turbines is truly environmentally friendly, how long it will take to address electricity distribution challenges, and whether clean energy systems function effectively. These questions require thorough investigation and should be central to future studies in environmental and energy economics.

CHAPTER 3

MODELING PERSISTENCE CHARACTERISTICS OF PRIMARY ENERGY CONSUMPTION FROM CLEAN RESOURCES, CONSIDERING ASYMMETRIES AND STRUCTURAL BREAKS

Chapter 3 examines the long-memory properties of clean energy shares in primary energy consumption for seven countries over the period 1950-2020. Clean energy encompasses both renewable and nuclear energy sources. Unlike previous studies, we analyze two clean energy series separately due to their differing sensitivities to external shocks and country-specific approaches. Recognizing that changes in regulatory policies, the implementation of new environmental laws, and potential market instabilities arising from major events can lead to structural breaks in the series, we employ a methodology that accounts for such breaks. In contrast to existing studies, our approach allows for smooth and instant breaks together, aiming to capture the accurate functional form of these breaks. We acknowledge that misspecification or ignoring these breaks can have severe consequences. Furthermore, to address the sign and size asymmetry of series' responses, which may stem from the break-even between adjustment costs and the burden of shocks, we employ a modified version of Quantile Unit Root procedures endogenizing the structural break terms. The results indicate that the series exhibit stationary behavior upon inclusion of the breaks, and these findings are country-specific. Our study provides reliable insights that can assist policymakers in shaping and achieving their policy objectives.

Keywords: Energy Economics, Persistence, Structural Breaks, Asymmetries

3.1. Introduction

The historical shift from wood to coal, then from coal to oil, and currently from fossil fuels to clean energy sources is termed energy transition. The latest shift is driven by concerns over energy sovereignty and environmental degradation. Clean energy, comprising renewable resources and nuclear energy, now accounts for approximately 18% of global primary energy consumption, with hydropower and nuclear energy leading at 6% and 4%, respectively, due to their long-standing presence. Solar and wind are viewed as modern renewables, demonstrating the highest consumption growth rates in the last 15 years due to increasing environmental concerns.

Several events have influenced these developments in the energy sector's history. Concerns about energy sovereignty emerged with the Suez Crisis in 1957, followed by the oil crises of the 1970s. Many countries turned to clean energy, particularly nuclear energy, as a hedge against oil supply uncertainties, resulting in a surge in clean energy research and developments in production technologies. The Three Mile Island Accident in 1979 and the Chernobyl Disaster in 1986 highlighted nuclear energy risks, causing a slowdown in nuclear energy consumption during the 1990s. Meanwhile, growing concerns about climate change spurred a global shift toward energy sources alternative to fossil fuels. International climate agreements like the Kyoto Protocol (2005) and the Paris Agreement (2015) aim to reduce emissions and promote sustainable energy, emphasized by social awareness and policies to mitigate climate impacts. Renewable energy has been favored over nuclear energy during this phase, particularly due to the inherent risks of nuclear energy and rapid declines in renewable energy prices due to technological advancements. Finally, the Fukushima Disaster in 2011 heightened concerns about nuclear energy, with production prices increasing, likely due to necessary safety measures, making nuclear energy less appealing.

Recent global economic developments, such as the 2008 economic crisis, the COVID-19 pandemic, and the Russian invasion of Ukraine in 2022, have raised concerns about slowing economic growth and shifted focus away from clean energy, resulting in increased fossil energy consumption. However, energy sovereignty remains a crucial 21st-century dilemma, underscoring the future importance of clean energy consumption.

Facing these events throughout the transition process, clean energy sector has gone through substantial changes. We aim to determine whether shocks to clean energy series result in permanent or transitory effects. In the context of stationary series, a temporary shock yields transitory effects and changes in moment conditions and deviations from the long-run growth path are typically short-lived. Conversely, if a series possesses a unit root, a temporary shock leaves a lasting impact, making it permanent. Furthermore, even in the case of stationary variables exhibiting mean-reverting behavior, the level of persistence dictates the duration it takes for the variable to return to its long-term mean. In instances where the series show persistence (long memory), temporary shocks exert long-term effects on moment conditions.

Long memory characteristics of energy variables are the determinants of policy and business decisions. That is why the literature of economics has a wide range of studies on the stationarity and persistence of energy variables. The studies using unit root tests to determine long memory in the energy literature are listed in Table 3.1.1. While some studies find stationarity (Narayan et al., 2007; Chen and Lee, 2007; Kula et al., 2012; Lean and Smyth, 2013; Shahbaz et al., 2013), there are other studies with unit root results (Hsu et al., 2008; Maslyuk et al., 2009; Golpe et al., 2012). Renewable energy studies that focus on sets of countries or resources also find mixed results (Gözgör, 2016; Demir and Gözgör, 2018; Cai and Menagaki, 2019; Aydın and Pata, 2020). While unit root tests are the first step to determine if the series show long memory, we need further estimations to find the level of persistence. Even when the series is found stationary it can show persistence, especially for close-to-unit root cases. To find the level of persistence in energy variables, literature resorted to Impulse Response Functions, Autoregressive (AR) coefficients, or half-life estimations (Özdemir et al., 2013; Belbutte and Pereira, 2017; Fallahi, 2019; Cai and Menegaki, 2019; Lee et al., 2019; Lee et al., 2021). However, previous work couldn't reach a consensus if the energy variables are transitory or persistent. Until more robust estimation techniques are developed, it is not plausible to rely on the existing results for policy or market decisions. That is why researchers try to apply newly developed, more efficient methodologies to explain the stochastic characteristics of energy variables.

The knowledge of persistence properties provides valuable insights for policy design, adopting a two-sided approach. When dealing with a stationary series featuring low persistence, policy shocks require long-lasting policies to achieve the desired outcomes. In such scenarios, undesired shocks lead to temporary effects as well, offering reassurance to policymakers and the market. In the presence of a unit root in the series, both positive and negative shocks are permanent. Consequently, when faced with an undesirable temporary shock, policymakers can employ one-time policy tools to mitigate the undesired impact. In cases where a time series exhibits long memory, short-term policies yield long-term effects. Hence, political and market decisions should align with the long-memory behavior of an economic time series. This study aims to contribute to consistent political design through robust empirical analyses particularly focusing on the long memory of energy variables and its implications for the broader economy.

There are several incentive policies designed to develop clean energy production and consumption, including feed-in tariffs; fixed bonuses[2]; renewable portfolio standards; investment, production, and sales tax credits; eliminating subsidies for fossil energies; and net metering to sell excess electricity to the grid rather than on-site storage (Lee et al., 2021).

Because policy implementation is costly for governments, if the policies are not designed well, unnecessary government spending with high costs will burden society. In terms of policy design according to dynamics of clean energy indicators, policies like production tax credits and investment tax credits promote the growth of clean energy production, but they deliver one-time shocks, which is useful only if the variable shows long memory. A clean energy portfolio standard that requires increasing the clean energy shares every consecutive year, results in continuous shocks, which is useful when the series is stationary, or the long memory parameter is low (Barros et al., 2013). In addition, we cannot offer a “one for all” type of policy as each country has its own energy transition path. That is why we need country-specific

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[2] Feed-in tariffs (FITs) provide renewable electricity producers with guaranteed payments for their production and feed into the grid. These payments are typically set at a rate above the market price, ensuring a steady and predictable return on investment for renewable energy projects. Fixed bonuses provide additional payments on top of FITs, to produce electricity from a specific energy source or to supply energy during a higher demand period.

studies rather than widely exercised panel studies like Chen and Lee, 2007; Hsu et al. 2008; Narayan et al., 2008; Mishra et al., 2009; and Lean and Smyth, 2013.

Information on stationarity and persistence of a time series is required further to make forecasts for future planning, which is crucial for evidence-based policymaking. International environmental policies have faced challenges in meeting their targets, often resulting in countries failing to fully comply with their commitments (Nordhaus, 2015). Interestingly, macroeconomic theories offer differing viewpoints on the long-term effects of such policies. Neoclassical Growth Theory posits that policy interventions are exogenous, suggesting that external shocks have only transient effects on long-term growth paths. Conversely, Endogenous Growth Theory argues that policies can exert permanent, long-term effects, particularly when considering factors like capital accumulation and research and development (R&D). The apparent contradiction in theories suggests the need for more effective policies, emphasizing the importance of diligent efforts during political design and implementation.

This study marks the pioneering effort to underline the significance of analyzing clean energy “shares” series rather than focusing solely on consumption or production levels. Reducing GHG emissions requires increasing the “amount of energy consumption from clean resources”. In the meantime, “total energy consumption”, especially from fossil fuels, should be decreased under the energy efficiency agenda where total energy consumed per unit of production should be lowered. Thus, what we need to focus on here should be increasing the share of clean energy in total energy consumption.

We claim that a relevant study on the long memory of energy variables with a focus on environmental concerns should be based on the clean energy shares series. Considering current climate change policies that aim to promote clean energy consumption, prioritizing only the increase in clean energy usage does not necessarily indicate progress toward environmental preservation. This is because policies that boost clean energy consumption without addressing the simultaneous or even greater increase in fossil fuel consumption can lead to an energy mix that remains, or even becomes more, harmful. Consequently, the objectives of reducing emissions and mitigating global warming may not be achieved. However, if the policy target is to increase the share of clean energy, the energy mix will gradually shift towards cleaner sources. While fossil fuel consumption might still rise, it would do so at a slower rate compared to the growth of clean energy, indicating a substitution of cleaner energies for more harmful ones. Therefore, the use of clean energy share is a more effective metric for policy assessment from multiple perspectives.

Another contribution of this study, in terms of using the most suitable variables representing clean energy and correctly addressing policy implications, is analyzing nuclear and renewable energy series both separately and comparatively, unlike the majority of existing studies. While previous studies on the persistence of energy series have examined clean energy, renewable energy, or nuclear energy, individually (Barros et al., 2012- 2013; Zuo and Guo, 2016; Shahbaz et al., 2018; Cai and Menegaki, 2019; Lee et al., 2019-2012), the importance of analyzing nuclear and renewable energy series together has not been explored to date. This importance arises from the varying behavior exhibited by these series in response to exogenous shocks. The behavioral divergence also differs from one country to another, making country-specific analyses a more essential means of gaining comprehensive insights.

We aim to establish a robust statistical foundation for designing policies that promote clean energy, specifically questioning whether the associated policy changes should be one-time or permanent adjustments. Existing research on the stationarity and persistence of energy variables often lacks comprehensive insights into how these statistical dynamics align with the nature and types of required policies. Notably, certain studies offer misleading conclusions, such as the assertion by Cai and Menagaki (2019) that when a series demonstrates stationarity, no policy will have impact. Similarly, Lee et al. (2021) suggest that in the presence of a unit root, temporary shocks will have only minor effects. Moreover, the origin of structural breaks is frequently misinterpreted. For example, a study on nuclear energy by Zuo and Guo (2016) finds the year 2011 as a structural break, attributing it only to the Fukushima Disaster for all countries. Some countries in their study, such as China, increased nuclear consumption following 2011. In China, 2011 represents nuclear-promoting policy interventions, unrelatedly coinciding with the Fukushima incident, resulting in an increase rather than a decrease in the nuclear energy consumption. Our objective is to address these notable gaps in the existing literature, focusing on identifying suitable variables for representing clean energy and ensuring accurate interpretations of policy implications.

After Perron (1989) perception of unit root testing has changed. According to Peron's statement most macroeconomic series face infrequent shocks that result in permanent changes in the series which can be identified as structural changes, such as the 1973 oil crisis. He argues that if unit root tests do not take structural breaks into account, a stationary process with breaks may be misperceived as a unit root process. Without incorporating nonlinearities caused by structural breaks, linear AR parameters are usually upward biased. Total and clean energy consumption series show structural breaks caused by many types of shocks such as wars, political unrest or instability and regulatory policies towards fuel efficiency, combination of fuels, prices of energy carriers, environmental law etc (Cai and Menagaki, 2019; Fallahi, 2020; Zsurkis et al., 2021). In our sample of the period 1950-2020, certain events affecting the global energy sector include: First (1972-1973) and second (1977-1978) global oil crisis, 1980 oil glut caused by low economic activity and energy conservation after oil crisis, First Gulf war (1990-1991), Asian financial crisis (1997), Second Gulf war (2003) and global economic crisis (2008). Kyoto Protocol Process (1997-2005) and Paris Agreement (2015) are also the main turning points for the sector to evolve towards cleaner energy use. Nuclear energy series faced the specific types of shocks that affected both the immediate amount of supply and societal viewpoint against nuclear energy: the Three Mile Island Accident (1976), the Chernobyl Accident (1986) and the Fukushima Disaster (2011). These accidents had spillover effects on the whole energy sector. Studies for energy variables in Table 3.1.1 show that when structural breaks are accounted for stationarity results increase and persistence decreases (Narayan et al., 2008; Hasanov and Telatar, 2011; Golpe et al., 2012; Lean and Smyth, 2013; Özdemir et al., 2013; Burakov and Dimitri, 2019; Cai and Menegaki, 2019).

Some of the events mentioned above can be treated as exogenous, however, each country has its own reaction process towards individual events. Country-specific policy schemes prior to these events or resulting governmental or social reactions will endorse country-specific structural break dates inside each economic system. Thus, treating breaks as unknown and endogenous is technically more relevant. In Perron’s 1989 study, exogenous structural breaks occur both in intercept and trend in instant break format. In the literature, instant breaks and the unit root testing are exercised by many studies: endogenizing instant breaks, Zivot and Andrews (1992), Lumsdaine and Papel (1997); using breaks in both null and alternative hypothesis, Lee and Strazicich (2003), Narayan and Popp (2010), Kim and Perron (2009); fitting the breaks with minimizing the sum of squared residuals instead of minimizing the unit root test statistic, Carrion-i Silvestre et al. (2009) and Carrion-i Silvestre and Gadea (2015). The characteristics of these tests are explained in detail in the methodology section.

In the context of economic time series, it may not be suitable to assume that all structural changes happen instantaneously. Typically, changes in aggregate macroeconomic series are realized by the actions of numerous individual actors. It is not likely that all these actors respond simultaneously to shifts in market conditions. Different types of agent behavior and institutional structure such as long-term or short-term contracts will determine the process and time-lag of the reaction (Leybourne et al., 1996). Also, the time span of the renewable energy policies (feed-in tariffs, fixed bonuses and renewable portfolio standards) is usually around 15 years, to protect new projects (Menanteau et al 2003). The existence of long-term contracts and policies justifies the use of smooth breaks even for yearly data. Kara et al. (2023) use both the Carrion-i Silvestre and Sanso (2007) sharp break stationarity test and the Becker et al. (2006) smooth break stationarity test on the non-renewable resource prices comparatively. They emphasize the need for the consideration of smooth and sharp breaks to avoid any misspecification of the functional form of the breaks, which could be as problematic as ignoring the breaks. They also address the need to account for smooth and sharp breaks jointly in unit root testing. In the literature, smooth breaks are either approximated by exponential/logarithmic smooth transition models (Leybourne et al., 1996; Sollis, 2004) or by Fourier components (Becker et al., 2006; Enders and Lee, 2012a). The characteristics of these tests are explained in the methodology section.

It is widely accepted that the macroeconomic time series follow nonlinear processes

(Granger and Tera ̈svirta, 1993; Leybourne et al, 1996). According to Hasanov and Telatar (2011) the nonlinearities caused by structural breaks and asymmetries in the models for energy variables stem from adjustment costs. If there is an exogenous shock, such as an energy price increase, firms will want to decrease their energy consumption through technical development. However, this development process will also be costly. If the adjustment costs are higher than the costs from energy price increase, authorities will not want to transform their technology and vice versa. Thus, from the data analysis point of view if the deviation from the equilibrium (old technology) is small (almost no change in old technology), energy consumption may not revert to the equilibrium mean. However, if the deviation is large (technological change adopted), energy consumption may revert to equilibrium. This type of asymmetry can be explained by Quantile Unit Root analysis.

A crucial question about the long memory behavior of energy variables is whether the series show the same level of persistence in response to small shocks and big shocks or negative shocks and positive shocks (Lee et al., 2019). This is relevant to energy variables such that a policy implementation towards reduction of total energy consumption is thought to be a negative shock to the series while a sudden reduction of oil prices or increase of energy demand is a positive shock. On the other hand, the response of the series, for instance, to a small or a large amount of increase in taxes for inefficient energy consumption or to a small or a large amount of subsidy promoting renewable energy consumption, is also relevant. Policymakers or businesspeople would like to know whether the impact of shocks in such characteristics is different. The most likely answer to this question is that they should be. However, analyzing the long memory properties provides information on the magnitude of this difference.

The method enabling these inferences on persistence dynamics is a novel approach introduced by Koenker and Xiao (2004), known as the Quantile-Based Unit Root Test (henceforth QUR). As they point out, if an innovation distribution deviates from the normal distribution, conventional unit root tests using Ordinary Least Square (OLS) regression exhibit poor power performance. Furthermore, non-normal distribution and heavy-tail properties are considered stylized facts for economic time series. Therefore, one needs to resort to unit root tests with non-normal innovations (Li and Park, 2018). OLS estimation focuses on the mean responses of a series. We can describe the mean and the quantiles as particular centers of a distribution minimizing a squared sum of deviations in the OLS and a weighted (by quantile check function) absolute sum of deviations in Quantile Regression (QR), respectively. For QUR, as well as for OLS, the parameter estimates in linear models are interpretable as rates of changes. The coefficient of interest, say β_i, can be interpreted as the rate of change of the τ-th quantile of the dependent variable distribution per unit change in the value of the regressor "i" (Davino and Furno, 2014; Waldman, 2017).

Given the potential non-standard distributions of inference test statistics and conditional quantiles, QUR necessitates the use of bootstrap methods to enhance the reliability of the results. Since we incorporate structural breaks in our quantile regression model, importance of using bootstrap critical values become emphasized. That is because limiting distribution of the test statistics is affected by the number and position of the structural breaks (Carrion-i Silvestre and Gadea, 2015). Galvao (2009) expanded QUR to have a linear trend in the stationary alternative.

Close relation of clean energy series with natural factors gives rise to concerns about unequal variation due to some complex interactions that cannot be measured or accounted for in statistical analysis. Unequal variation implies that there is more than a single response describing the relationship between a dependent variable and predictor variables measured on a subset of these factors. Quantile Regression helps tackle this problem by looking for various responses through the different parts of the probability distribution of the variable of interest (Cade and Noon, 2003). In their study on US renewable energy consumption, Lee et al. (2019; 2021) use QUR and they find large or moderate shocks have longer-lasting effects, also, negative shocks have longer memory than positive shocks.

While there are unit root tests accounting for smooth and sharp breaks, and QUR is dealing with asymmetries, the next area of expansion is the need for incorporating structural breaks into QUR methodology. Lee et al. (2019) use Nonlinear QUR (NQUR) and Fourier QUR (FQUR) in their study. NQUR is suggested by Li and Park

(2018). They use well-known ESTAR nonlinearity in the alternative hypothesis of QUR test. In ESTAR type of models, the nonlinearity is imposed in the stochastic component of the series. So, they actually do not deal with the smooth structural breaks in the deterministic part but the nonlinearity in the AR process. In FQUR nonlinearity is fed to the deterministic part of the OLS regression in Fourier terms.

Bahmani-Oskoee and Wu (2018) add sharp break terms to FQUR as trend and intercept dummies and find Fourier Frequencies and coefficients of all break terms simultaneously by grid search based on the SSR of the model regression by using Bai and Perron (henceforth BP) Test (1998; 2003). After the deterministic part is modeled, they substract that part of the regression (detrending) and look for the unit root in the remaining part (residuals) with QUR.

We need to mention the pioneering study on structural breaks in Quantile Autoregressive model of Koenker and Xiao (2004). Qu (2008) and Oka and Qu (2011) test for multiple unknown structural changes on the conditional quantiles rather than conditional mean with a method motivated by BP Test. Additionally, they test if certain structural changes affect all quantiles. They analyze the Blood Alcohol Concentration (BAC) series from the crash cases data of Highway Traffic Safety Administration. Their study reveals that the law for minimum drinking age in 1984 cannot be captured as a break for the high quantiles (0.85 or higher). Furthermore, their findings suggest that the policies are more effective for ‘‘light drinkers’’ than for ‘‘heavy drinkers’’.

Tillman and Wolters (2014) use Qu (2008) structural breaks model with QUR. They look for structural breaks in the persistence parameter (sum of AR coefficients), not in trend or intercept, of their unit root regression. They find that while some breaks can be detected for some quantiles and not for others, some breaks can be detected for all quantiles. After finding a common break date in persistence for all quantiles (by DQ test of Qu (2008)), they fragment the series into subsets by the determined break and look for asymmetric persistence in conditional quantiles with QUR. They find that when breaks are considered, inflation has a unit root before the 1980s but is stationary after the 1980s for all conditional quantiles.

The methodology of this study is another distinctive contribution. From Qu (2008), Oka and Qu (2011), and Tillman and Wolters (2014) we can infer that structural breaks have quantile-specific impacts. Then, their effect on persistence should be quantile-specific as well. Thus, we need a methodology that endogenizes both sharp and smooth structural breaks in the deterministic component for all individual quantiles throughout the QUR process to see the asymmetries in persistence. We have tailored the QUR test so that we can endogenously identify the structural breaks. In our modified QUR analysis of energy series the part of the regression with structural breaks, the deterministic part, is not eliminated before unit root estimation as in widely used FQUR (see Özcan and Öztürk, 2016; Cai and Menegaki, 2019; Lee et al, 2019; 2021). Rather we employ sharp and smooth breaks in each quantile to see if allowing for those breaks suppress quantile specific persistence responses.

Table 3.1.1 provides an in-depth review of the existing literature on the dynamics of energy variables and relevant research on structural breaks and unit roots. Numerous studies have extensively examined the unit root behavior of energy variables, with a particular focus on energy consumption. The first segment of Table 3.1.1 provides a comprehensive list of some of these studies. The prevailing findings in much of them indicate that the incorporation of structural breaks tends to induce stationarity in energy variables. Recognizing the pivotal role of structural breaks in explaining the stochastic nature of energy variables, contemporary literature has ventured into modeling the functional forms of these breaks. This includes the exploration of smooth transitions using Fourier or exponential/logarithmic threshold forms, in addition to incorporating sharp break components such as trend and intercept dummies. Furthermore, researchers have studied nonlinear responses to shocks, aiming to provide a more comprehensive understanding of energy variables. Second segment of Table 3.1.1 presents the studies involving various methodologies to determine structural breaks.

It is posited that the time series data exhibits heterogeneous dynamics. Time series variables may display asymmetric persistence responses, spanning the entire distribution of the series. To address these distributional properties, Quantile Unit Root Test (QUR) is developed by Koenker and Xiao (2004). In the third segment of Table

3.1.1, we briefly introduce the QUR methodology. Fourth group of studies on Table 3.1.1 are the studies on structural breaks in Quantile Regression and QUR framework. Most of the energy literature is built on the unit root properties of energy variables. However, it is argued that ADF type tests have low power compared to the tests with fractional roots (Lean and Smyth, 2009). Fractional Integration methods are promising if the researcher does not want to comply with the distinction between I(0) – I(1) and explicitly model the long memory stochastic characteristics of a time series. In such cases interpretation of long-memory behavior has various aspects (Dolado et al, 1989; Lobato and Velasco, 2007; Geweke and Porter-Hudak, 1990; Sowell, 1992; Robinson, 1994; Shimotsu and Philips, 2005). Fifth segment of Table 3.1.1. presents such studies.

The remainder of the study is organized as follows. Section 3.2 describes our dataset and presents country-specific trends in clean energy consumption. Section 3.3 offers a comprehensive discussion on methods for measuring long memory and details the QUR methodology and our modified QUR test. Section 3.4 reviews the results of conventional unit-root tests, with and without structural breaks, and models each country's clean energy share series with both sharp and smooth breaks. The empirical results of the QUR test and the modified QUR test are then presented. Section 3.5 concludes the study.

Table 3.1.1 Literature on energy economics and relevant methods

Article	**Year**	**Timeline**	**Variable**	**Method**	**Results**
			Unit Root in Energy Variables		
Narayan et al.	2007	1979-2000	Energy Consumption pc	T-bar Test for panel data (Im et al (2003))	Stationary
Chen and Lee	2007	1971–2002	Energy Consumption pc	Panel unit root test (Carrion-i-Silvestre et al. (2005)), wt structural breaks	Stationary
Hsu et al.	2008	1971-2003	Energy Consumption	Panel SURADF (Breuer et al. (2001, 2002))	Mixed but mainly non-stationary
Narayan et al.	2008	1971-2003	Crude Oil and NGL Production	Panel unit root test without structural breaks (Breitung (2000), Im et al. (2003), Levin et al. (2002), Maddala and Wu (1999), Hadri (2000)) and LM Unit Root Test (Im et al. (2005)) wt 1 structural break	Inconclusive without structural breaks, Stationary wt structural breaks

Table 3.1.1. (continued)

Maslyuk et al	2009	1/1973-12/ 2007	Crude Oil Production	Test for non-linearity, then TAR (Threshold Auto-Reg) Unit Root methodology (Caner and Hansen (2001)), wt 2 regimes	Non-stationary
Mishra et al	2009	1980-2005	Energy Consumption pc	Panel unit root test (Carrion-i-Silvestre et al. (2005)), wt structural breaks	Mixed results by countries, Stationary for panel
Aslan and Kum	2011	1970-2006	Energy Consumption	Linearity test (Harvey et al. (2008)) LM Unit Root Test (Lee and Strazicich (2003)), wt at most 2 structural breaks for linear variables Kruse Test (2011) for non-linear variables.	Linear: Stationary, Non-linear: non-Stationary
Hasanov and Telatar	2011	1980-2006	Energy Consumption	Conventional Unit root tests/ New unit root tests with nonlinearity (Kapetanios et al., 2003) and structural breaks (Sollis, 2004)	Stationarity results increase as nonlinearities considered and increased further wt structural breaks
Narayan and Liu	2011	1976 – 2010, daily	Commodity prices	Unit Root Tests (Narayan and Popp, 2010; Liu and Narayan, 2010), wt 2 structural breaks	Mixed results
Golpe et al	2012	–973:1 - 2010:3	Natural gas consumption	ADF and Ng–Perron test (2011) for stationarity. Linear and non-linear unobserved components model estimated via MLE using Kalman filter.	Non-stationary. Long memory shows after a threshold value.
Kula et al	2012	1960-2005	Energy Consumption	LM Unit Root Test (Lee and Strazicich (2003)), wt at most 2 structural breaks	Mixed but mainly stationary
Lean and Smyth.	2013	1978-2010	Energy Demand	LM Unit Root Test (Schmidt and Phillips (1992) and Lee and Strazicich (2003, 2004)), wt 0, 1 and 2 structural breaks	Mixed, Stationary wt structural breaks
Lean and Smyth.	2013	1980-2008	Renewable Electricity Generation: Malaysia	Unit Root Tests (Levin et al. (2002), Maddala and Wu (1999) and Im et al. (2003)) Panel Unit Root Tests (Carrioni-i-Silvestre et al. (2005) and Hadri (2000), wt structural breaks)	Mixed but mainly non-stationary wt Panel Unit Root Tests
Meng et al.	2013	1960-2010	Energy Consumption pc	2-step LM and 3-step RALS-LM Unit Root Tests (Lee et al. (2012) and Meng and Lee (2012)), wt 2 structural breaks	Mixed but mainly stationary
Özdemir et al	2013	1/1991 – 12/2011	Brent Crude Oil spot and futures prices	A grid bootstrap procedure (by Hansen, 1999) to estimate sum of AR coefficients, allowing for 3 structural breaks wt trend or intercept dummies (Lumsdaine and Papel, 1997, Unit root test)	Persistence decreases when str. br. allowed.
Shahbaz et al.	2013	1971-2010	Electricity Consumption pc	LM Unit Root Test (Lee and Strazicich (2003, 2004)), wt at most 2 structural breaks	Stationary
Gözgör	2016	1971-2014	Renewable Energy Consumption: Brazil, China, and India	Unit Root Test (Lee and Strazicich (2003, 2013); Narayan and Popp (2010)), wt 1 and 2 str br Unit Root Test wt multiple str br (Carrioni-i-Silvestre et al. (2009)	Mixed results

Table 3.1.1. (continued)

Demir and Gözgör	2018	1971-2016	Renewable Energy Consumption: 54 developing and developed countries	Narayan and Popp (2010)), wt 2 str br	Stationary in 45 of 54 countries
Ghoshray, Atanu	2018	1/1986 – 3/2016	Energy prices: Crude oil, natural gas, coal, gasoline, heating oil	Test for structural breaks (by Perron and Yabu (2009) and Harvey et. al. (2009)) Test for constant unconditional variance (breaks) (by Inclan and Tiao (1994) and Sanso et. al. (2004)) Unit root test (by Cavaliere et. .al (2011) and Smeekes and Taylor (2012)) Decomposition to permanent and transitory components (by Sinclair (2009))	Structural breaks in prices and variances. Nonstationary.
Burakov, Dimitry	2019	1990-2017	Crude Oil Production	LM Unit Root Test (Lee and Strazicich (2003)), wt at most 2 structural breaks	Stationarity results increase with structural break.
Aydın and Pata	2020	1/1973-9/2019	US Disaggregated Renewable Energy Consumption	Discrete Wavelet Transformed Unit Root Test wt Fourier structural breaks	Consumption from Hydropower is stationary, others are not.

Structural Breaks and Nonlinearity in Unit Root Tests

Perron	1989	1860 (or later)-1970 1941:1-1986:3	Nelson-Plosser postwar data (14 macro series) (62-111 data points) Real GNP	DF on y as an AR process. Breaks are known and given exogeneously. Null hyp: Model A: $y_t = \alpha_1 + y_{t-1} + dD(TB)_t + \varepsilon_t$ Model B: $y_t = \alpha_1 + y_{t-1} + (\alpha_2 - \alpha_1)DU_t + \varepsilon_t$ Model C: $y_t = \alpha_1 + y_{t-1} + dD(TB)_t + (\alpha_2 - \alpha_1)DU_t + \varepsilon_t$ $D(TB)_t = 1\ if\ t = T_B + 1, 0\ otherwise$ $DU_t = 1\ if\ t > T_B, 0\ otherwise$ $\varepsilon_t\ follows\ ARMA$ Alternative hyp: Model A: $y_t = \alpha_1 + \beta_1 t + (\alpha_2 - \alpha_1)DU_t + \varepsilon_t$ Model B: $y_t = \alpha_1 + \beta_1 t + (\beta_2 - \beta_1)DT^*{}_t + \varepsilon_t$ Model C: $y_t = \alpha_1 + \beta_1 t + (\alpha_2 - \alpha_1)DU_t + (\beta_2 - \beta_1)DT_t + \varepsilon_t$ $DT^*{}_t = t - T_B$ $DT_t = t\ if\ t > T_B\ and\ 0\ otherwise (growth)$ $DU_t = 1\ if\ t > T_B, 0\ otherwise\ (level)$ Testing series has a unit root with an exogenous one time change at T_B vs series is stationary around a deterministic trend with an exogeneous change occurring at the trend at time T_B.	Stationary when structural breaks are accounted for.

Table 3.1.1. (continued)

Zivot and Andrews	1992	1860 (or later)-1970 1941:1-1986:3	Nelson-Plosser postwar data (14 macro series) (62-111 data points) Real GNP	Argues that the exogeneous fitting of the break dates is data dependent. Provides invariance of the t-statistic distribution to the break parameters by excluding the break terms from the null hypothesis. Null hyp for all models in Perron (1989): $y_t = \alpha_1 + y_{t-1} + \varepsilon_t$ Unknown date is chosen as the date that gives the minimum t-statistic for unit root testing. Unit root with breaks under the alternative hyp. leads to spurious rejections of unit root null.	Stationarity results increase when the break point is estimated endogenously. Results slightly change compared to Perron (1989)
Leybourne et al	1996	1860 (or later)-1970	Nelson-Plosser postwar data (14 macro series) (62-111 data points)	Non-linear LS, then, ADF on residuals to look for unit roots. Allows for one intercept and one trend break. Null hyp: $y_t = \varepsilon_t$ $\varepsilon_t = \varepsilon_{t-1} + e_t$ Alternative hyp: Model C (most general): $y_t = \alpha_1 + \beta_1 t + \alpha_2 S_t(\gamma, \tau) + \beta_2 t S_t(\gamma, \tau) + \varepsilon_t$ $S_t(\gamma, \tau) = [1 + \exp\{-\gamma(t - \tau T)\}]^{-1}$ Estimates NLS parameters by minimizing SSR of Models A (break in intercept, without trend), B (break in intercept, with trend) and C (break in both intercept and trend).	Stationarity results increase when structural breaks are accounted for.
Lumsdaine and Papel	1997			ZA (1992) test with 2 structural breaks: $y_t = \alpha_0 + \beta_0 t + \theta_1 DT_{1,t} + \gamma_1 DU_{1,t} + \theta_2 DT_{2,t} + \gamma_2 DU_{2,t} + \alpha_1 y_{t-1} + \sum_{i=1}^{k} \beta_i \Delta y_{t-i} + \varepsilon_t$ $DU_{i,t} = 1 \; if \; t > T_{B,i}, 0 \; otherwise$ $DT_{i,t} = t - T_{B,i} \; if \; t > T_{B,i}, 0 \; otherwise$ $T_{B,i}$: time of the break Criticized because it allows unit root with breaks cases under the alternative hyp. Leads to spurious rejections of unit root null.	
Bai and Perron	1998	Simulation		$y_t = x_t{}'\beta + z_t{}'\delta + \varepsilon_t$ x: vector of non-shifting variables z: vector of shifting variables Obtain β and δ, minimizing the SSR: $\sum_{i=1}^{m+1} \sum_{t=T_i-1}^{T_i} [y_t - x_t{}'\beta - z_t{}'\delta]^2$ Estimated break points are the ones minimizing the above SSR with m+1 partitions. Tests if δs are different.: • No breaks vs a fixed number of breaks • Sequentially tests l vs l+1 breaks for the shifting variables.	Presents a treatment for the presence and number of multiple structural changes.

Table 3.1.1. (continued)

Kapetanios et al	2003	1957:1-2000:3 1957:1-1998:4	US Real interest rates 11 Real exchange rates with US Dollar	Non-linearity only. DF Test: $\Delta y_t = \gamma y_{t-1}[1 - \exp(-\theta y_{t-1}^2)] + \varepsilon_t$ $H_0: \theta = 0$ $H_1: \theta > 0$ Uses: $\Delta y_t = \delta y_t^3 + err$ To estimate t-statistics under the null $\theta = 0$. $t = \frac{\hat{\delta}}{se(\hat{\delta})}$ Non-linearity is imposed on y_t.	Stationarity results increase when nonlinearity is accounted for.
Lee and Strazicich	2003	1860 (or later)-1970	Nelson-Plosser postwar data (14 macro series) (62-111 data points)	Argues that ZA Test does not imply stationarity when the unit root null is rejected because alternative hypothesis has a possible case that could result in unit root with breaks. Addresses the need of breaks in null hypothesis argument of Perron (1989) and endogenous breaks argument of Zivot and Andrews (1992). LM Unit Root test (Schmidt and Philips (1992)) on y. $\Delta y_t = \Delta x_t{}'\beta + S_{t-1}'\phi + \varepsilon_t$ $S_t = y_t - \psi_x - x_t{}'\beta$ $\psi_x = y_1 - x_1{}'\beta$ $H_0: \phi = 0$ $x_t = \alpha_0 + \beta_0 t + \theta_1 DT_{1,t} + \gamma_1 DU_{1,t} + \theta_2 DT_{2,t} + \gamma_2 DU_{2,t}$ $DU_{i,t} = 1\ if\ t > T_{B,i}, 0\ otherwise$ $DT_{i,t} = t - T_{B,i}\ if\ t > T_{B,i}, 0\ otherwise$ $T_{B,i}$: time of the break Breaks are determined minimizing the LM test statistic: t statistic for $\phi = 0$.	Stationarity results increase when breaks are accounted for. More breaks compared to ZA(1992), less breaks compared to Perron(1989).
Sollis	2004	1/1960-4/1998	Industrial Production in UK and US	One trend break, one intercept break. Approximates both smooth and sharp breaks $y_t = \alpha_1 + \beta_1 t + \alpha_2 S_t(\gamma,\tau) + \beta_2 t S_t(\gamma,\tau) + \varepsilon_t$ $S_t(\gamma,\tau) = [1 + \exp\{-\gamma(t - \tau T)\}]^{-1}$ Estimate residuals from the above regression. Then, $\Delta\hat{\varepsilon}_t = I_t \alpha_1 \hat{\varepsilon}_{t-1} + (1 - I_t)\alpha_2 \hat{\varepsilon}_{t-1} + \sum_{i=1}^{p} \beta_i \Delta\hat{\varepsilon}_{t-1} + \eta_t$ $I_t = 1\ if\ \hat{\varepsilon}_{t-1} \geq 0, I_t = 0\ if\ \hat{\varepsilon}_{t-1} < 0, \eta_t\ WN$ t-test or F-test if $\alpha_1 = 0\ and/or\ \alpha_2 = 0$ for stationarity of y.	UK series is only stationary wt Sollis's test. US series is stationary wt conventional tests and Sollis's test.
Becker et al.	2006	1973–2003	Simulation Quarterly nominal exchange rates against the US dollar: Canada, Japan and UK	KPSS Test DGP: $y_t = \alpha_0 + \alpha_1 t + \sum_{n=1}^{N} \lambda_n \sin\left(\frac{2\pi k_n t}{T}\right) + \sum_{n=1}^{N} \gamma_n \cos\left(\frac{2\pi k_n t}{T}\right) + \varepsilon_t$ $\varepsilon_t = \rho\varepsilon_{t-1} + e_t$ Optimal frequency k is estimated by SSR minimization.	Stationarity results increase when nonlinearity is accounted for with Fourier components.

Table 3.1.1. (continued)

Carrion-I Silvestre et al. Carrion-I Silvestre and Gadea	2009 2015	J/1948 -11/2014	Simulation Monthly US unemployment rate	Addresses the power and size concerns raised by ZA. Allows breaks both under null and alternative hyp. Tests for unit root with (only in 2009 study) Feasible Point Test statistic (Elliot et al., 1996), M-Class of test statistics (Ng and Perron, 2001) and (only in 2015 paper) a pseudo ADF t-ratio statistic. Determines unknown break date estimates by minimizing the SSR of the GLS-detrended model (2009) and OLS model (2015) following Bai and Perron (2003) methodology.	Evidence against unit root hypothesis is weaker when structural breaks and bounds are accounted for.
Narayan and Popp	2010			Test equations are similar to LP (1997) and LS (2003). $y_t = \alpha_0 + \beta_0 t + \delta_1 D(T_{B,1}) + \delta_2 D(T_{B,2}) + \theta_1 DT_{1,t} + \gamma_1 DU_{1,t} + \theta_2 DT_{2,t} + \gamma_2 DU_{2,t} + \alpha_1 y_{t-1} + \sum_{i=1}^{k} \beta_i \Delta y_{t-i} + \varepsilon_t$ $D(T_{B,i}) = 1\ if\ \ t = T_{B,i}, 0\ otherwise$ $DU_{i,t} = 1\ if\ t > T_{B,i}, 0\ otherwise$ $DT_{i,t} = t - T_{B,i}\ if\ t > T_{B,i}, 0\ otherwise$ $T_{B,i}$: time of the break DF type test: t statistic for $\alpha_1 = 1$ Selects the break dates by maximizing the significance (t-statistic) of the break dummy coefficient δ.	More accurate detection of break dates compared to LP and LS. Better size and power properties.
Enders and Lee	2012	1/1990-11/2003	US 3 months T-Bill rate, 1 year and 3 years rates	LM unit root test (Schmidt and Philips (1992)) Fourier terms with single frequency (n=1) and integer ks. DGP: $y_t = \alpha_0 + \alpha_1 t + \sum_{n=1}^{N} \lambda_n \sin\left(\frac{2\pi k_n t}{T}\right) + \sum_{n=1}^{N} \gamma_n \cos\left(\frac{2\pi k_n t}{T}\right) + \varepsilon_t$ $\varepsilon_t = \rho\varepsilon_{t-1} + e_t$ $H_0: \rho = 1$ $H_1: \rho < 1$	T-Bill and 1-year rates are stationary wt Fourier approximation.
Omay and Yıldırım	2013	6/2003-10/2011	Monthly exchange rate wt USD for PPP Hypothesis: Argentina	$y_t = \alpha_1 + \alpha_2 S_t(\gamma, \tau) + \varepsilon_t$ $S_t(\gamma, \tau) = [1 + \exp\{-\gamma(t - \tau T)\}]^{-1}$ $Get\ residuals$: $\hat{\varepsilon}_t = y_t - \alpha_1 - \alpha_2 S_t(\gamma, \tau)$ Then Kepatenios et al. (2003) KSS test on $\Delta\hat{\varepsilon}_t = \phi\hat{\varepsilon}_t^{\ 3} + \sum_{i=1}^{p} \beta_i \Delta\hat{\varepsilon}_{t-1} + \eta_t$ $H_0: \phi = 0$: Linear non-stationary $H_1: \phi < 0$: Non-linear and stationary around non-linear trend and intercept	Stationary with new test
Omay	2015	Simulation		Fractional Freq Fourier DF Test. $\Delta y_t = \alpha_0 + \alpha_1 t + \phi y_{t-1} + \lambda_k \sin\left(\frac{2\pi kt}{T}\right) + \gamma_k \cos\left(\frac{2\pi kt}{T}\right) + \varepsilon_t$ $H_0: \phi = 0$ $H_1: \phi \neq 0$	k may take fractional values.

Table 3.1.1. (continued)

Özcan and Öztürk	2016	1971-2013	Energy Consumption pc in 32 OECD countries	Bahmani Oskoee and Wu, 2014: $y_t = \alpha + \beta T + \sum_{l=1}^{m+1} \theta_l DU_{l,t} +$ $\sum_{k=1}^{n} \lambda_k \sin\left(\frac{2\pi kt}{T}\right) + \sum_{k=1}^{n} \gamma_k \cos\left(\frac{2\pi kt}{T}\right) + \varepsilon_t$ $U_{l,t} = 1\ if\ TB_{l-1} < t < TB_l, 0\ otherwise$ Chooses n=1 and looks for optimal k (integer) and m.	Mixed results: 16 Mean-reverting, 16 not.
Shahbaz et al	2018	1800-2008	Renewable Energy Consumption: Canada, 1800-2008; France, 1800-2008; Germany, 1815-2008; Italy, 1861-2008; Netherlands, 1800-2008; Portugal, 1856-2008; Spain, 1850-2008; Sweden, 1800- 2008; The UK, 1800-2008	NLS: 3 Models: $y_t = \alpha_1 + \alpha_2 S_t(\gamma, \tau) + \varepsilon_t$ $y_t = \alpha_1 + \beta_1 t + \alpha_2 S_t(\gamma, \tau) + \varepsilon_t$ $y_t = \alpha_1 + \beta_1 t + \alpha_2 S_t(\gamma, \tau) + \beta_2 S_t(\gamma, \tau) + \varepsilon_t$ $S_t(\gamma, \tau) = [1 + \exp\{-\gamma(t - \tau T)\}]^{-1}$ Gets residuals: $\hat{\varepsilon}_t = \alpha_0 + \sum_{k=1}^{n} \lambda_k \sin\left(\frac{2\pi kt}{T}\right) +$ $\sum_{k=1}^{n} \gamma_k \cos\left(\frac{2\pi kt}{T}\right) + \phi \varepsilon_{t-1} + v_t$ Then, Fourier DF on $\hat{\varepsilon}_t$ by Enders and Lee. (2012)	Stationary with new test.
Cho	2018	12/1988-6/2016	Forward premium of 6 currencies	STAR. Tests for additional breaks by adding $[\mu_m + \phi_m\, LCOE_{t-1}] \times\ G(z_t; \gamma_m, c_m)$ terms once at a Time. $x_t = \mu_0 + \phi_0\, x_{t-1} + \sum_{m=1}^{M} [\mu_m + \phi_m\, x_{t-1}] \times$ $G(z_t; \gamma_m, c_m) + \varepsilon_t$ $G(z_t; \gamma_m, c_m) = [1 + \exp\left(-\gamma_m (z_t - c_m)\right)]^{-1}$ MLP Regression for estimating FI parameter. Sums the ϕ_m parameters coming from each break as a measure of persistence.	Persistence reduced wt structural breaks.
Asymmetric Persistence Response					
Koenker and Xiao	2004		Nelson and Plosser Data: US 1-month, 3-month and yearly interest rates	Quantile ADF function for an AR(p) process: $Q_{y_t}(\tau \mid \mathcal{F}_{t-1}) = Q_u(\tau) + \alpha_1(\tau) y_{t-1} +$ $\sum_{j=1}^{q} \alpha_{j+1}(\tau) \Delta y_{t-j}$ $Q_{y_t}(\tau \mid \mathcal{F}_{t-1}) = x_t{}' \alpha(\tau)$ Minimizes quantile check function: $\min_{\alpha \in R^2} \sum_{t=1}^{n} \rho_\tau \left(y_t - x_t' \alpha(\tau)\right)$ $\rho_\tau(u) = u(\tau - I(u < 0))$ Uses $\alpha_1(\tau)$ at different quantiles as persistence measure. Uses resampling to approximate small sample and non-standard distn' of the test statistic. Quantile Unit Root test for individual quantiles. $Q_u(\tau) = \alpha_0(\tau)$ tests if $\alpha_1 = 1$ by the t-statistic $t_n(\tau) = \frac{\hat{f}(F^{-1}(\tau))}{\sqrt{\tau(1-\tau)}} (y_{-1}' M_z y_{-1})^{\frac{1}{2}} (\widehat{\alpha_1}(\tau) - 1)$ QKS test over a range of quantiles. $QKS = sup_{\tau \epsilon \Gamma} \lvert t_n(\tau) \rvert$	Asymmetric responses across quantiles. Higher accuracy.

Table 3.1.1. (continued)

Structural Breaks in Quantile Regression					
Qu	2008		Simulation	Tests for multiple unknown structural changes on the conditional quantiles rather than conditional mean. Consider: $Q_{y_t}(\tau \mid \mathcal{F}_{t-1}) = Q_u(\tau) + \alpha_1(\tau) y_{t-1} + \sum_{j=1}^{q} \alpha_{j+1}(\tau) \Delta y_{t-j}$ $Q_{y_i}(\tau \mid x_i) = x_i{}' \alpha_i(\tau)$ Let y_i and x_i (y_j and x_j) denote subsamples. Tests if $\alpha_i(\tau) = \alpha_j(\tau)$. 1)Test with sub-gradient (sub-sample up to a certain point in series) 2)Test with subsamples.	Recommends sub-gradient type test for small samples. Tests for the change in all parameters.
Oka and Qu	2011	–947:2 - 2009:2 1983–2007	Quarterly US real GDP growth rates Individual quarterly blood alcohol concentration (BAC) data on young drivers involved in motor vehicle accidents	Qu (2008) structural breaks model with QUR	In GDP series higher quantiles are affected. In BAC series coefficient change is higher in lower quantiles.
Tillman and Wolters	2014	1947:2-2013:4	US inflation data: • quarter on quarter %change in CPI • month on month %change in CPI • quarter on quarter %change in PCE • month on month %change in PCE • quarter on quarter %change in GDP deflator	Uses QUR Then Qu (2008) structural breaks model with QUR Looks for the breaks in persistence parameter not in trend and intercept. When a break is found, the persistence analysis is done by fragmenting the series into subsets by the determined breaks and looking for asymmetric persistence in conditional quantiles.	There are breaks in the persistence of inflation series. When breaks are considered, inflation has unit root before 1980s but stationary after 1980s.
Bahmani-Oskoee and Wu	2018	1/1994-3/2016	Real Exchange Rate for PPP Hypothesis	FQUR smooth and sharp breaks. $y_t = \alpha + \beta T + \sum_{l=1}^{m+1} \theta_l DU_{l,t} + \sum_{l=1}^{m+1} \rho_l DT_{l,t} + \sum_{k=1}^{n} \lambda_k \sin\left(\frac{2\pi kt}{T}\right) + \sum_{k=1}^{n} \gamma_k \cos\left(\frac{2\pi kt}{T}\right) + \varepsilon_t$ $DU_{l,t} = 1\ if\ TB_{l-1} < t < TB_l, 0\ otherwise$ $DT_{l,t} = t - TB_{l-1}\ if\ TB_{l-1} < t < TB_l, 0\ otherwise$ Chooses n=1 and looks for optimal k and m. **Detrends the data getting the residuals from the above regression.** Then Quantile Regression on residuals: $Q_\tau(\hat{\varepsilon}_t \mid \hat{\varepsilon}_{t-1}, \dots, \hat{\varepsilon}_{t-q}) = \alpha(\tau)\hat{\varepsilon}_{t-1} + \alpha(\tau) + \sum_{i=1}^{q-1} \phi_i(\tau) \Delta\hat{\varepsilon}_{t-i}\ ;\ \tau \in (0,1)$ Unit root test on $\alpha(\tau) = 1$ with t-statistic proposed by Koenker and Xiao (2004) and Galvao (2009)	Stationarity in 18 of 34 countries compared to 0 in 34 with conventional tests.

Table 3.1.1. (continued)

Cai and Menegaki	2019	1965-2016	Clean energy (sum of nuclear and renewable) consumption in emerging economies: Brazil, China, India, Indonesia, Malaysia, Pakistan, Philippines, and Thailand	Unit root tests wt structural breaks: Zivot and Andrews (2002), Lumsdaine and Papel (1997), Lee and Starizich (2003) FQUR only smooth breaks: Bahmani-Oskoee and Wu, 2018 Half-life for quantiles.	Stationarity results increase with smooth breaks. Mixed country specific results.
Lee et al.	2019	1/1973-8/2019	US Renewable Energy production disaggregated (by source)	FQUR only smooth breaks: Bahmani-Oskoee and Wu, 2018 NQUR: Li and Park (2018) $y_t = \alpha_1 + \alpha_2 t + \varepsilon_t$ Then estimate residuals and unit root test. $\hat{\varepsilon}_t = \phi {\hat{\varepsilon}_{t-1}}^3 + \sum_{p=1}^{p=1} \beta_{1+p}\, Q\hat{\varepsilon}_{t-p} + \eta_t$ H_0: $\phi = 0$: *unit root* H_1: $\phi < 0$: Then non-linear quantile unit root test: $Q_{\hat{\varepsilon}_t}(\tau \mid \vartheta_{t-1}) = \phi_0(\tau) + \phi_1(\tau){\hat{\varepsilon}_{t-1}}^3 + \sum_{p=1}^{p=1} \phi_{1+p}\, Q\hat{\varepsilon}_{t-p} + \eta_t$ Estimates Growth Stability.	Stationarity in aggregate and disaggregated series. Negative shocks have longer memory than positive shocks.
Lee et al.	2021	1960-2017	US Renewable Energy consumption pc	FQUR only smooth breaks: Bahmani-Oskoee and Wu, 2018	Stationary for 32 States. Negative shocks have longer memory than positive shocks.
Fractional Integration					
Lean and Smyth	2009	1/1973 – 7/2008	US Petroleum Consumption by sectors	LM Tests for FI (Nielsen, 2005) $(1+L)^{d+\theta} y_t = e_t I(t \geq 1), \quad t = 0, \pm 1, \pm 2, \ldots$ H_0: $\theta = 0$ H_1: $\theta \neq 0$	Mixed persistence and integration results
Gil-Alana et al	2010	1/1973-3/2009	Energy Consumption by Electric power source	$y_t = \alpha_j + \beta_j t + x_t;\ (1-L)^d x_t = u_t;\ \phi_s(L^s)u_t = \varepsilon_t$: Seasonal AR disturbances $y_t = \alpha_j + \beta_j t + x_t;\ (1-L^s)^{d_s} x_t = u_t;\ \phi_s(L)u_t = \varepsilon_t$: Seasonal long memory Estimate d and d_s by LW (Dahlhaus, 1989) Robinson's LM Test for FI: H_0: $d = d_0$ and H_0: $d_s = d_{s0}$ s=12, monthly wt and without a single break (Gil-Alana, 2008)	Mixed results. Stationarity increases after breaks introduced.
Apergis and Tsoumas	2012	1989-2009	Fossil, coal and electricity consumption	FI with a known break (Robinson 1994, Gil-Alana 2002)	Stationary (d<05) also non-stationary with low persistence (0.5<d<1).

Table 3.1.1. (continued)

Barros et al	2012	–981:1 - 2010:10	US Renewable Energy consumption	FI (Daulhaus 1989, Robinson 1994)	Non-stationary with mean reversion.
Barros et al.	2013	2/1994-10/2011	US disaggregated (by source) Renewable Energy Consumption	Local Whittle Estimation Roninson's LM Test Uses Gil-Alana (2008) methodology for str breaks.	Mixed results. Most non-stationary.
Gil-Alana and Gupta	2014	9/1859 – 10/2013	Oil Prices	FI, Estimates d by a Whittle function (Dahlhaus, 1989; Fox and Taqqu, 1986; Robinson, 1994)	There is FI if cycles are accounted for.
Gil-Alana et al.	2016	28/2/2007-14/5/2014	CO_2 Emissions allowance prices	Non-linearity by Chebyshev Polynomials Structural Breaks with multiple d's. (Fractional Integration) $y_t = \sum_{i=0}^{m} \theta_i P_{iT}(t) + x_t \quad t = 1,2,\ldots$ $P_{0T}(t) = 1$ $P_{iT}(t) = \sqrt{2}\cos\left(\frac{i\pi(t-0.5)}{T}\right)$ $(1-L)^{d_0} x_t = u_t$ And Multiple d's As in Gil-Alana (2005)	Persistence reduced if str breaks are accounted for.
Belbutte and Pereira	2017	1751-2014	Global CO_2 emissions from fossil fuels by source	ADF test ARFIMA: MLE by Sowell, 1992 ARFIMA on the whole sample Chow Test for a known structural break ARFIMA on the split samples before and after the break date. Impulse Responses	Stationary long memory (0<d<0.5) Higher d on the period after break.
Gil-Alana and Solarin	2018	1940-2014	US emissions	One d with sharp breaks. Also, multiple d's. $y_t = \alpha_1 + \beta_1 t + \alpha_2 I(t > T^*) + \beta_2 (t - T^*) I(t > T^*) + x_t$ $(1-L)^d x_t = u_t$ Estimates d with LW (Dahlhaus, 1989). Then tests for d with Robinson's LM (1994). Also, $y_t = \alpha_1 + \beta_1 t + x_t;\ (1-L)^{d_1} x_t = u_t$ $y_t = \alpha_2 + \beta_2 t + x_t;\ (1-L)^{d_2} x_t = u_t$ Introduces each break at a time and compares before and after estimations. Estimates d's with Gil-Alana (2008) methodology. Minimizes SSR imposing a single break for every t. (like Bai and Perron, 2003)	Nonstationary without str breaks. Mixed results wt structural breaks.
Bozoklu et al.	2020	1971-2014	Energy Consumption pc	Fourier ADF of Enders and Lee (2012) wt Omay Fractional Fourier (2015) EFDF Lobato and Velasco (2007) Robinson's LM test for FI with Fractional Fourier (Gil-Alana and Yaya, 2020) Only smooth breaks	Stationarity results increase wt Fourier components

3.2. Data

This study aims to model the persistence of the share of renewables and the share of nuclear energy series. We claim that the persistence of these series exhibits asymmetric behavior in response to positive or negative shocks, as well as small or large shocks. Furthermore, we highlight the importance of incorporating both sharp and smooth break terms to achieve a more precise analysis of the persistence patterns in the shares of renewables and nuclear energy series. The data source of this study is "World Energy Consumption A Database 1820-2020" (Malanima, 2022) that is published at Harvard University, Joint Center for History of Economics.[3] This comprehensive database covers a wide range of countries. For the purpose of our empirical analysis, we focus on the following countries: China, the US, France, Brazil, Germany, Japan, and the UK. The time frame of the study covers the years 1950 to 2020.

Before the 1950s, the consumption of clean energy was not significant, and the availability of data for that period was limited. Most of the existing literature primarily relies on data from 1965 onwards. However, when employing econometric techniques to estimate break dates accurately in clean energy series, it is crucial to have an earlier start date. This allows for a more precise examination of breaks, particularly to assess if the oil crisis of the 1970s can be captured adequately. Using data from 1950 to 2020 in this study provides a suitable time interval for such purposes. Our analysis contends that the series of renewable and nuclear energy underwent three major structural changes during this period. The first occurred during the 1970s oil crisis, the second during the implementation and aftermath of the Kyoto Protocol in the 2000s, and the third following the Fukushima Nuclear Disaster in 2011. These events should have influenced countries to increase their clean energy consumption in response to the oil crisis and the Kyoto Protocol, while subsequently witnessing a decline in nuclear consumption levels due to security concerns following the Fukushima incident.

The analysis starts by focusing on the top 10 countries with the highest clean energy consumption as of 2020. These countries serve as the driving forces behind the clean energy sector, and studying their responses to major events is of great significance. The countries included in this list are China, the United States, France, Brazil, Germany, Russia, Canada, India, Japan, and the United Kingdom.

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[3] The full dataset is obtained upon request from Professor Malanima.

Figure 3.2.1 depicts the series of total primary energy consumption. For most countries, until the 2000s, primary energy consumption showed predominantly positive trends. However, a notable decline can be observed in the early 1980s for the United States, France, Germany, Japan, and the United Kingdom - all developed countries at that time. This decline coincided with the oil glut resulting from reduced economic activity following the oil crisis of the 1970s. Additionally, the decrease in energy consumption in Russia around 1990 corresponds to the dismantling of the Union of Soviet Socialist Republics (USSR). Another significant observation is the relatively small decline followed by a recovery in energy consumption, for almost all countries due to the 2008 Global Economic Crisis. Furthermore, the end of each country series reveals a decline in energy consumption in 2020 attributed to the COVID-19 pandemic. In recent years, there has been a notable decrease in energy consumption growth among the countries included in this list.

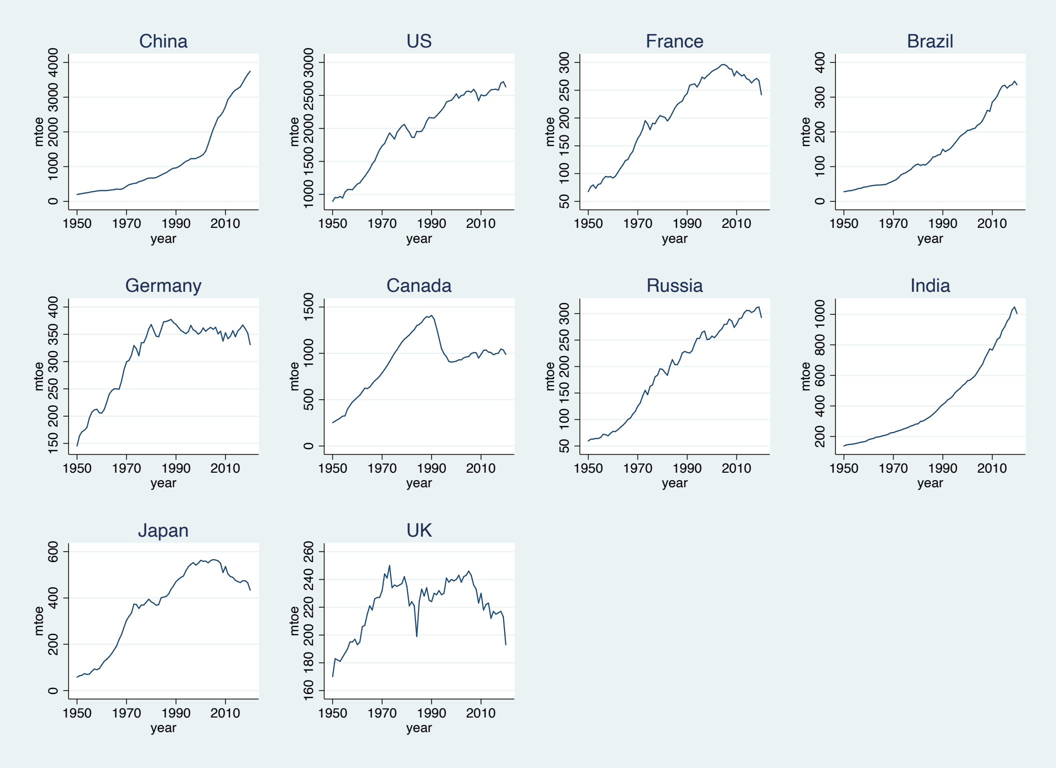

Figure 3.2.1 Total Primary Energy Consumption

This decline can be attributed to the influence of environmental concerns and the global energy efficiency movement. However, it is worth noting that three countries, namely China, Brazil, and India, have experienced continued growth in energy consumption. These countries are classified as developing nations and are exempt from the more stringent terms of the Kyoto Protocol. Reducing energy consumption serves as a foundational element in environmental policies aimed at achieving lower greenhouse gas (GHG) emissions. Furthermore, countries must prioritize the promotion of clean energy consumption to expedite the decline in GHG emissions and address environmental challenges effectively.

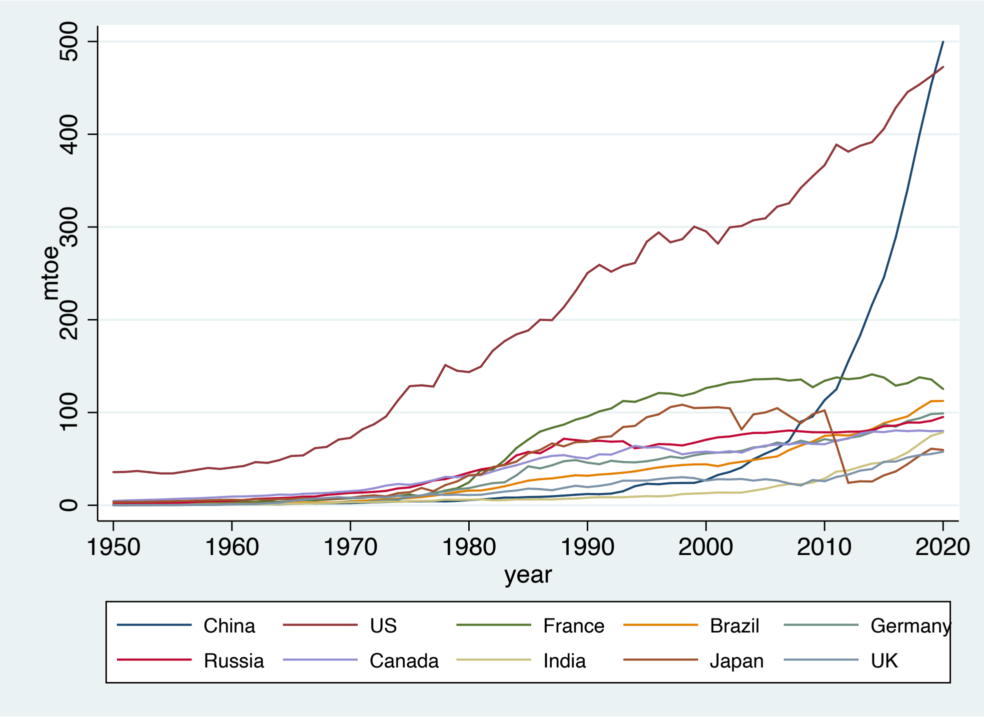

Figure 3.2.2 Clean Energy Consumption

Figure 3.2.2 illustrates the sectoral dominance of the United States over the years and the subsequent rise of China, which has surpassed the US in recent times. The clean energy consumption levels of other countries in the list remain lower when compared to China and the US. It is important to note that data presented in Figure 3.2.2 accounts for aggregate clean energy consumption for each country, without considering per capita consumption. This distinction is crucial as it acknowledges that the overall consumption levels of China and the United States cannot be disregarded due to their substantial contributions to the clean energy sector.

Examining the timeline from 1950 to 2020, we observe an overall positive trend shift following the oil crisis of the 1970s. China experienced a remarkable surge in clean energy consumption during the 2000s, while Japan faced a decline following the Fukushima Nuclear Disaster in 2011. These events further highlight the dynamic changes that have shaped the clean energy series throughout the examined period.

The focus of this study is on clean energy, which includes both renewable and nuclear energy sources. Unlike the majority of the existing literature, we prefer to analyze renewables and nuclear energy separately and comparatively. This approach is due to the observation that these two energy sources follow distinct paths in response to various historical energy events. This differentiation allows for a deeper understanding of the unique dynamics and patterns of each energy source. For instance, it is notable that many countries opted to prioritize nuclear energy following the Oil Crisis while placing less emphasis on renewable energy sources. By examining renewables and nuclear energy independently, we gain insights into their individual trajectories and influencing factors.

Furthermore, the Fukushima Disaster had contrasting effects on the renewable and nuclear energy series. If we were to use aggregate clean energy consumption as the sole variable of analysis, we would not be able to accurately observe the true impact of such events. Additionally, the opposing directions of change in renewables and nuclear energy consumption would cancel each other out, leading to an inaccurate representation of the overall dynamics.

Another crucial observation is that the renewable and nuclear energy series follow distinct paths for each country. This implies that country-specific factors play a significant role in shaping their energy choices and consumption patterns. For instance, in the aftermath o’ the 1970s' Oil Crisis, while many countries leaned towards nuclear energy, Brazil opted to replace oil with renewables. Therefore, relying solely on aggregate clean energy consumption would not provide reliable insights into the country-specific changes and variations in energy sources. By analyzing renewables and nuclear energy separately, we can capture the nuanced dynamics and country-specific responses to different events, enabling a more comprehensive understanding of the factors influencing energy choices and consumption patterns.

In this regard, Figures 3.2.3 and 3.2.4 indeed provide valuable insights into the dynamics of renewable and nuclear energy consumption. These figures enable clear observation of the immediate increase in nuclear energy consumption during the 1970s, while renewable energy consumption remained relatively low until the 2000s.

The figures also facilitate easy comparisons between countries, with the United States and France consistently occupying the top positions in nuclear energy consumption, while China and the United States rank first and second in renewable energy consumption. It is noteworthy that China has shown a strong focus on both clean energy sources since the 2000s but with a greater emphasis on renewable energy rather than nuclear energy.

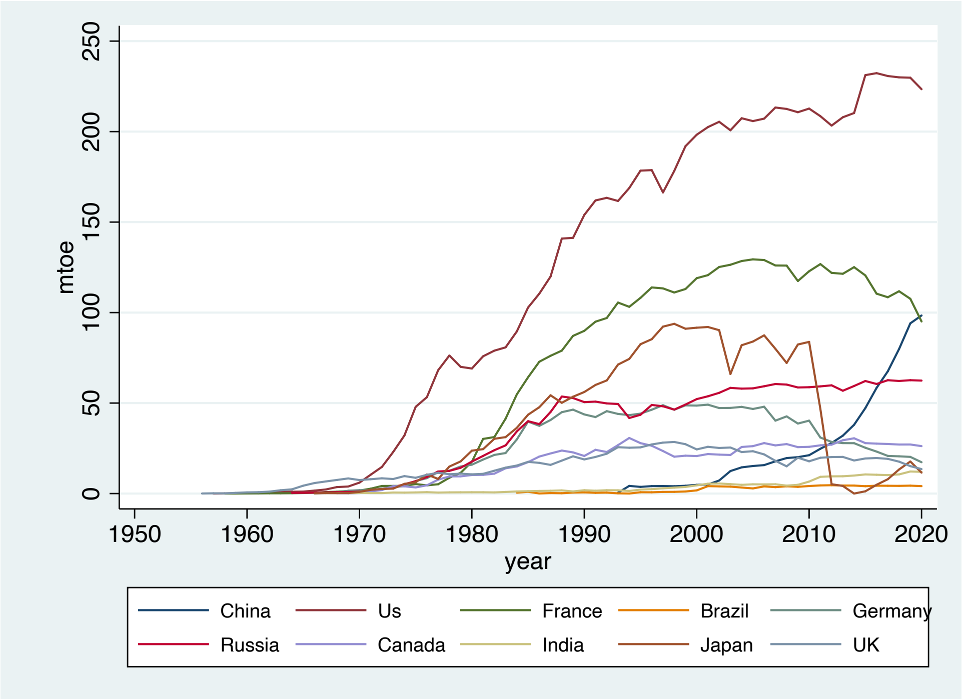

Figure 3.2.3 Nuclear Energy Consumption

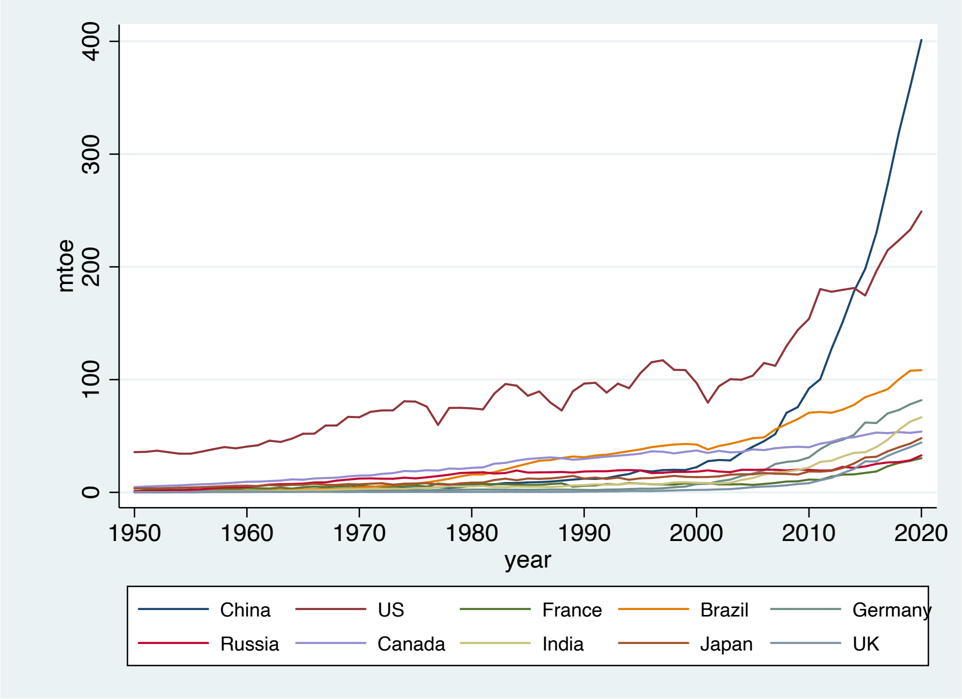

Figure 3.2.4 Renewable Energy Consumption

Figure 3.2.5 presents the combined view of renewable energy consumption and nuclear energy consumption for each country, providing a convenient platform for country-specific comparisons. Consistent with our earlier claims, we can observe that most countries increased either renewable or nuclear energy consumption in response t’ the 1970s' oil crisis. Subsequently, during the period of the Kyoto Protocol (1997-2005), the growth of renewable energy accelerated. It is notable that around the time of the Kyoto Protocol, many countries displayed reluctance in expanding their nuclear energy production. This hesitancy towards nuclear energy can be attributed to two major nuclear accidents in the 20th century: the Three Mile Island Accident in 1979 and the Chernobyl Accident in 1986. Following these incidents, regulations for nuclear facilities tightened, with project timelines extending up to 30 years (Faure, 2019). Another reason for the reluctance is the high cost of nuclear power. Nuclear energy's Levelized Cost of Energy (LCOE) has increased by 80% since 2010, making it less economically attractive compared to other energy sources (Lazard Capital, 2023).

A remarkable observation is that, except for China, all the countries in this group have experienced a decline or slowdown in nuclear energy consumption in the 21st century.

Among the 10 countries analyzed, France, Brazil, Germany, Japan, and the UK are particularly noteworthy as they have actively reduced their reliance on nuclear energy following the Fukushima Disaster in 2011. Germany, in fact, has decided to completely phase out nuclear energy by 2022, with the date of implementation being April 16, 2023, albeit slightly prolonged due to the natural gas shortage following the Russian invasion of Ukraine in 2022.

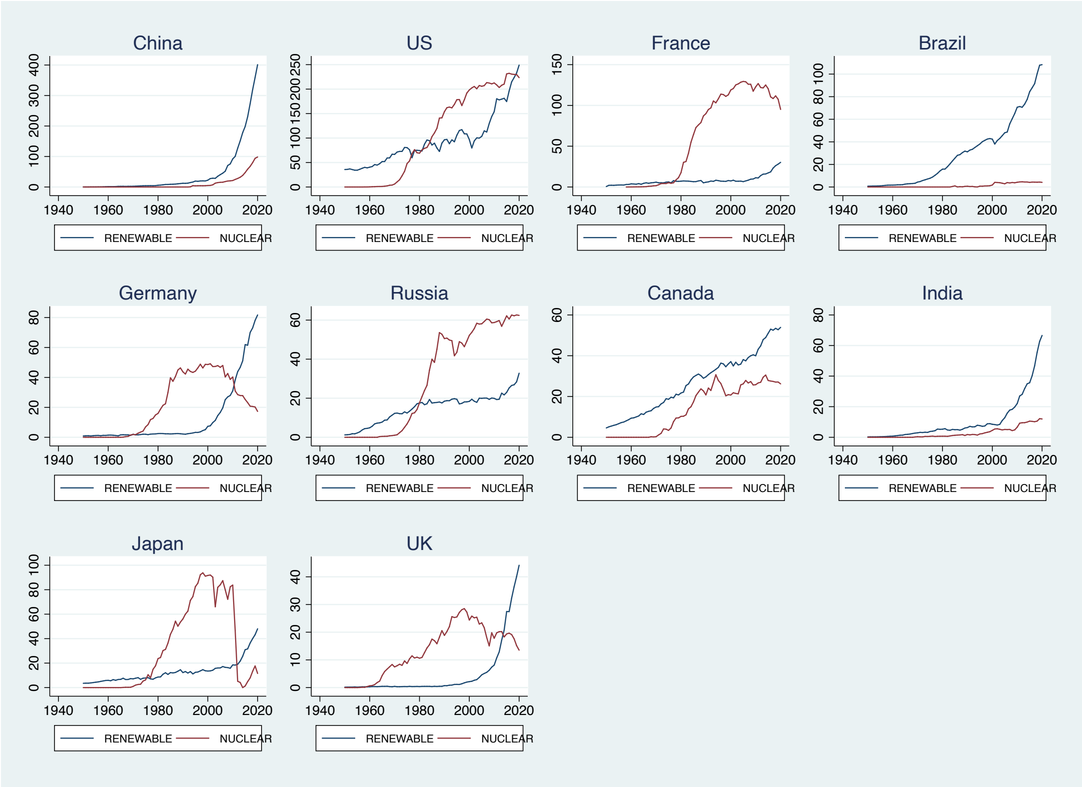

Figure 3.2.5 Renewable Energy and Nuclear Energy Consumption (mtoe)

It is important to recognize that nuclear energy has both environmental benefits, as it provides greenhouse gas-free electricity, and environmental challenges, particularly in managing nuclear waste. The decision regarding nuclear energy involves careful considerations and trade-offs. For nuclear energy to become more popular, there needs to be an increase in fossil fuel prices, a technological breakthrough reducing costs of nuclear energy production, a decrease in financial and political risks, or alleviation of safety concerns (Jurewitz, 2002).

To facilitate meaningful comparisons, the analysis focuses on a selected group of 7 countries: China, US, France, Brazil, Germany, Japan, and the UK, using data spanning from 1950 to 2020. We aim to underscore the importance of dynamics of renewable energy series for better understanding its crucial role in environmental sustainability.

Additionally, the study seeks to explore the nuclear energy dilemma, which encouraged us to examine France, Brazil, Germany, Japan, and the UK with their declining nuclear energy consumption, in comparison to continued growth of nuclear consumption in China and the slowed nuclear consumption in the US. China and US are the first and second countries with the highest clean energy consumption, far above the other countries on the list. Further examination, with China and The US on the list, will greatly enhance our ability to draw meaningful conclusions on the clean energy consumption.

The data used in this study corresponds to energy consumption from primary resources, as defined by Malanima (2022). Primary electricity in the database represents electricity generated solely from renewable resources such as water, wind, geothermal, solar, and modern biofuels. Nuclear energy consumption is reported separately. The consumption series are measured in million tons of oil equivalent (mtoe).

The variables of interest in this study are the share of renewables in primary energy consumption (select) and the share of nuclear energy in primary energy consumption (snuclear). The focus on share series is motivated by the aim to assess progress towards a carbon-free world. The pursuit of an environmentally sustainable energy sector involves increasing energy efficiency by reducing overall energy consumption from any source and optimizing resource utilization. Merely relying on coal, oil, and natural gas does not represent the most efficient use of resources as they lack viable replacements. To save the environment and promote energy efficiency, it is essential to decrease total energy consumption while increasing the use of alternative, non-carbon-emitting resources. Therefore, analyzing the shares of clean resources in total energy consumption provides the most meaningful perspective from an environmentally conscious standpoint.

The study focuses on three major shocks to the shares series within the timeline: the Oil Crisis, the Kyoto Protocol, and the Fukushima Nuclear Disaster. While the Three Mile Island Accident (1979) and the Chernobyl Disaster (1986) are also significant events, they did not result in immediate and observable reactions, making them less suitable as break dates. Three Mile Island was caused by human error, and Chernobyl involved a specific reactor type used only in the Soviet Union, thus their impacts were limited (Steinhauser, 2014). In contrast, Fukushima, which was caused by an earthquake followed by a tsunami, highlighted nuclear vulnerability to natural disasters. Moreover, the timing of Fukushima coincided with advancements in renewable technologies, allowing countries to pivot away from nuclear energy.

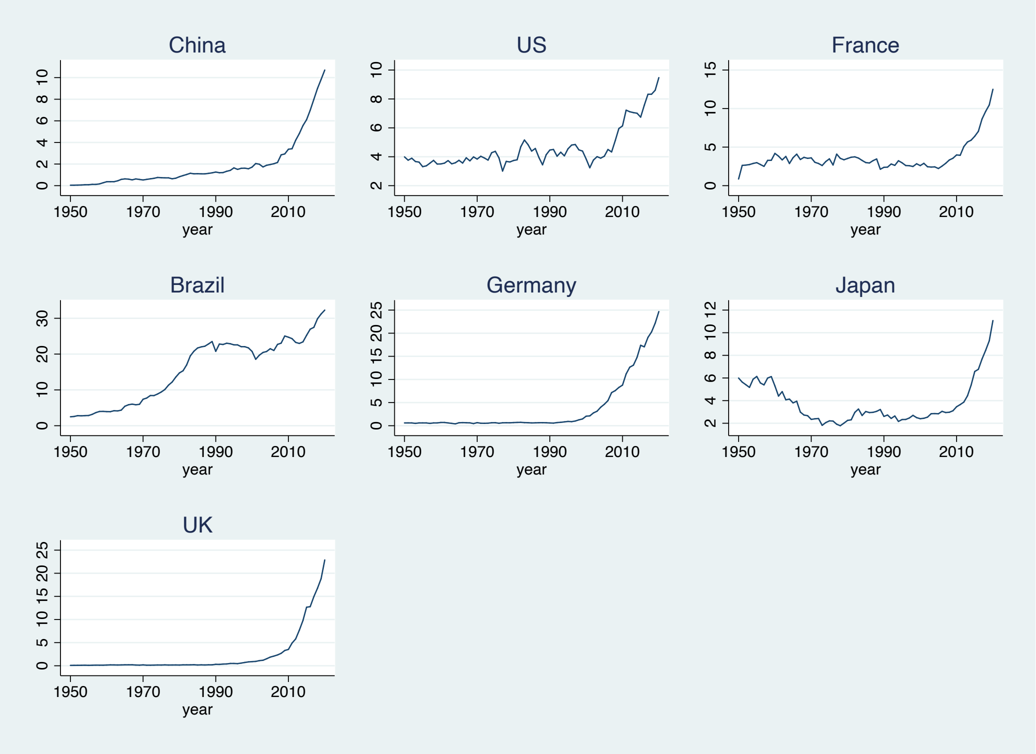

Figure 3.2.6 Share of Renewables in Primary Energy Consumption (%)

Although aggregate energy consumption has been influenced by the 2008 Economic Crisis and the COVID-19 pandemic, the impacts of these events on clean energy shares series are minor and transitory, thus not constituting significant structural breaks. As 2020 is the last data point, it is technically not possible to detect COVID-19 as a structural break. The Paris Agreement (2015) is another important change that could have a positive impact on clean energy consumption. However, due to the fact that the series were already on an increasing trend after the Kyoto Protocol, and the deviation from the previous trend is not substantial, 2015 cannot be detected as a structural break date.

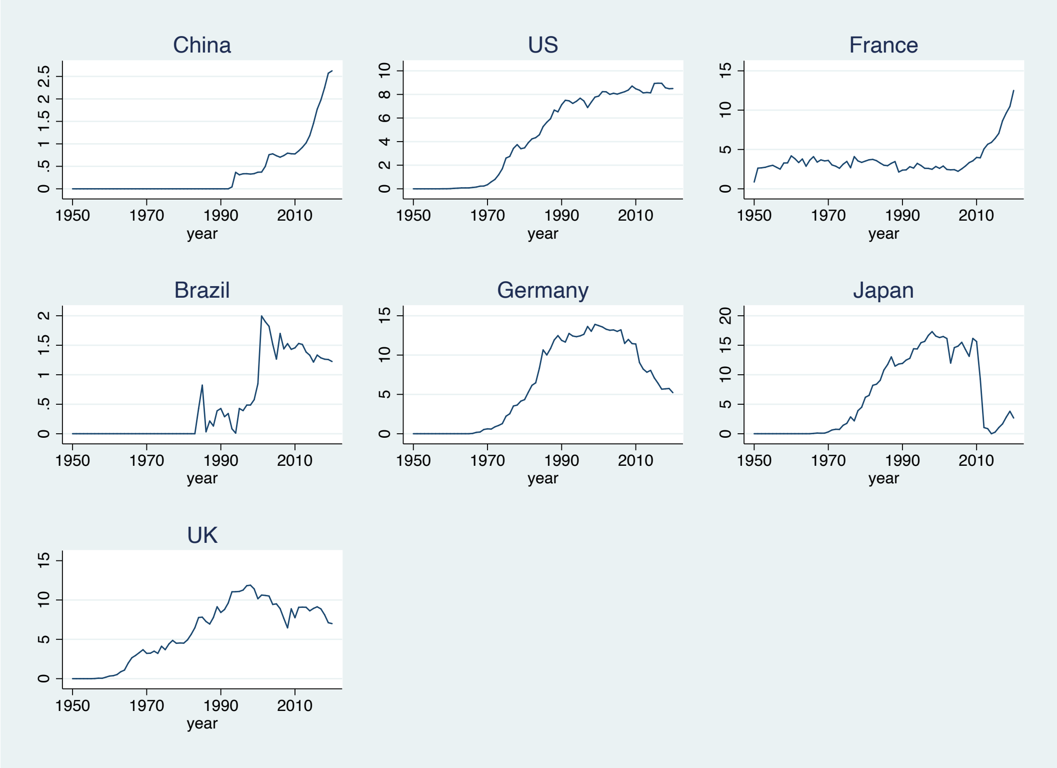

Figure 3.2.7 Share of Nuclear in Primary Energy Consumption (%)

The analysis of the shares series in Figures 3.2.6 and 3.2.7 reveals that renewables account for approximately 10% to 30% of total primary energy consumption in most countries. The share of nuclear energy is around 10% in many countries, except for France, where it reaches approximately 40%. France heavily relies on nuclear energy for achieving energy independence. It is worth noting that China and Brazil have relatively low shares of nuclear energy in their energy mix. Renewable energy has gained popularity over the past two decades, with significant growth observed during this period. Prior to that, renewable energy consumption was relatively low. On the other hand, nuclear energy was preferred by most countries since the 1970s. However, some countries have started decreasing their reliance on nuclear energy, while others have slowed down its growth in recent years The decline in nuclear consumption is primarily attributed to nuclear accidents, which have raised safety concerns and to increasing prices due to safety measures and increases in prices of baseline materials.

Table 3.2.1 Summary Statistics of Share of Renewables and Nuclear Energy in Primary Energy Consumption

Share of Renewables

select (%)	**# of Observations**	**Mean**	**Std Dev**	**Minimum**	**Maximum**
China	71	1.846	2.335	0.041	10.703
US	71	4.580	1.438	3.008	9.475
France	71	3.682	1.922	0.859	12.505
Brazil	71	15.578	8.945	2.492	32.285
Germany	71	3.683	6.038	0.399	24.684
Japan	71	3.794	1.894	1.783	11.077
UK	71	2.250	4.800	0.083	22.879

Share of Nuclear Energy

snuclear (%)	**# of Observations**	**Mean**	**Std Dev**	**Minimum**	**Maximum**
China	28	0.928	.705	0.042	2.625
US	61	5.272	3.278	0.01	8.954
France	63	25.122	18.909	0.001	46.198
Brazil	37	0.967	0.599	0.01	1.995
Germany	55	8.058	4.699	0.039	13.906
Japan	55	11.512	9.696	0.01	26.37
UK	65	6.422	3.576	0.016	11.881

As a result, countries that consider nuclear energy unsafe and expensive have shifted their focus towards renewable energy, leading to an increase in the share of renewables. It is worth noting that this is one of the reasons why the Kyoto Protocol is considered a break date especially for renewable energy but not for nuclear energy. By examining the shares series, one can observe both smooth and sharp breaks, indicating the non-stationarity of the series across all countries.

Table 3.2.1 presents the descriptive statistics. The dataset includes 71 data points for each country for renewable energy, covering the period from 1950 to 2020. We can observe that Germany, Brazil, and the UK are the leading countries in the share of renewable energy, while France, followed by Japan, has the highest shares of nuclear energy. Other than the UK and the US, almost none of the countries had nuclear energy consumption until around 1960. Brazil and China adopted nuclear energy even later, in 1984 and 1993, respectively. Therefore, nuclear energy series have different numbers of observations for each country.

3.3. Methodology

This section provides a brief review of the previous methodologies used to analyze long-memory and in particular persistence parameter. Then, the discussion on sharp and smooth breaks and asymmetric persistence responses, explained in the literature review part, is summarized focusing on clean energy series. The QUR process of Koenker and Xiao (2004) and the consequent methods in the literature to incorporate structural breaks in the QR framework; Qu (2008), Oka and Qu (2011) tests for multiple unknown structural changes on the conditional quantiles, as well as, Bahmani-Oskoee and Wu (2018) FQUR with smooth and sharp breaks, will be introduced. Finally, our QUR Test with smooth and sharp structural breaks will be demonstrated.

Long-memory of a time series denotes that the moment conditions like mean, variance and trend will change in case of seasonality, structural breaks and autocorrelations. Even if they revert to their previous values after the impact of any shock subsides, this process will take long. Below we will be explaining such phenomena for the energy series. The variability in moment conditions can be explained by statistical methods. Degrees of persistence of shocks to macroeconomic time series can be studied or estimated with: Unit Root Tests, Impulse Response Function (IRF), Largest Autoregressive (AR) coefficient, Sum of AR coefficients, Cumulative Impulse Response (CIR), Half-life, Fractional Integration (FI) parameter.

Unit root tests determine if a series is stationary or not. If a series is nonstationary, it has long memory. This interpretation is the first step in analyzing persistence. However, it is incomplete. Some stationary time series also show persistent behavior. The dynamics of a time series need to be analyzed to learn the characteristics in detail. IRF is the impact of a unit innovation applied to the series at some specific time. A drawback of impulse responses is that, if the process shows high persistence, we will not be able see the exact persistence process in an infinite MA representation. In such cases IRFs cannot give detailed interpretation about the behavior of the series, which is impractical (Baillie, 1996; Kapetanios, 2002). AR coefficients determine the impact of lagged values on the variable itself. Largest AR coefficient is considered a measure of long memory. However, the sum of AR coefficients is more reliable compared to the largest AR coefficient because two series with the same largest AR root may show different degrees of persistence (Baillie, 1996; Fallahi, 2018).

For an ADF regression, with the first lagged term and lagged differences, sum of AR coefficients (ρ) is equal to the coefficie^{nt} of the 1st lag, α.

$$y_t = \gamma + \beta t + \alpha y_{t-1} + \sum_{i=1}^{\rho} \phi_i \Delta y_{t-i} + \varepsilon_t \tag{3.3.1}$$

Cumulative impulse response (CIR) of an AR(p) process can be estimated as inverse of $(1-\rho)$ (Fallahi, 2019). The larger the ρ, the larger the cumulative impact of the shock will be. For $\rho > 1$, using sum of AR coefficients or CIR will not be able capture the shape of the long memory behavior.

Half-life is the number of periods for which the effect of a unit shock remains above 0.5 fraction of itself, estimated as:

$$Halflife = log(0.5)/log(\alpha) \tag{3.3.2}$$

where α is the sum of AR coefficients. In the case of oscillations half-life may underestimate the persistence. Also, computation is easy for an AR(1) process but not so for an AR(p) process (Dias and Marques, 2005; Cortareas and Kepatenios, 2013).

In fact, methods involving autoregressive roots and impulse response functions are alike in terms of the parameter of interest because cumulative impulse response function and half-life are calculated using the sum of AR coefficients (Fallahi, 2019). The Fractional Integration (FI) parameter is another measure for persistence helping in situations where order of integration of a series is neither 0 nor 1, which is not the case in our analysis.

Share of nuclear and renewable energy consumption series show structural breaks caused by many types of shocks such as wars, political unrest or instability and regulatory policies towards fuel efficiency, combination of fuels, prices of energy carriers, environmental law, etc. As each country responds to exogenous shocks differently, structural break dates will occur specifically characterized according to each economic system. Thus, treating breaks as unknown and endogenous is technically relevant. These breaks may emerge both in trend and intercept in instant break format since nuclear and renewable energy series face large supply shocks. On the other hand, they may show smooth break characteristics since these are macroeconomic series that are affected by aggregation of the unsynchronized responses of a large number of agents. Menu costs, long-term contracts, and policies also cause smooth breaks in clean energy series.

Visual examination of shares of renewable and nuclear energy data in Figures 3.2.6 and 2.2.7 reveal structural changes that manifest as distinct events on the timeline of a series, featuring sharp as well as smooth shifts in both trend and intercept. In this study, we identify sharp breaks by employing intercept and trend dummies, akin to Perron (1989). Methods designed to detect smooth structural breaks rely on Fourier terms or exponential smooth transition functions. We opt for the use of Fourier functional forms due to their ease of application.

After Perron's breakthrough literature has come up with various methodologies to determine the number and form of structural breaks. Zivot and Andrews (1992) (henceforth ZA) argue that the exogeneous fitting of the break dates is data dependent. Their method allows for one break and endogenizes the break. Unknown break date is chosen by sequential testing as the date that gives the minimum t-statistic for unit root test. Invariance of the t-statistic distribution to the break parameters is provided by excluding the break terms from the null hypothesis. Lumsdaine and Papel (1997) develops on ZA test allowing for two breaks. ZA tests if the series has a unit root without any structural change. Lee and Strazicich (2003) (henceforth LS) argue that ZA test does not imply stationarity when the unit root null is rejected because alternative hypothesis has a possible case that could result in unit root with breaks. Their study addresses the need of breaks in null hypothesis argument of Perron (1989) and endogenous breaks argument of Zivot and Andrews (1992). LS test provides invariance of the distribution of the test statistic to the break parameters in the null hypotheses by using LM test statistic. Breaks are determined minimizing the LM test statistic.

ZA, LS or Narayan and Popp (2010) type tests which estimate the break dates minimizing the associated unit root test statistic or t-statistics of the break dummy coefficients are criticized because of the concerns about consistency and convergence rates. Use of a break date different from the true one leads to a misspecified trend function causing inconsistency. When the break date is estimated by minimizing the sum of squared residuals (SSR) of the test regression these concerns are satiably addressed (Kim and Perron, 2009). In their unit root tests, Carrion-i Silvestre et al. (2009) and Carrion-i Silvestre and Gadea (2015) determine unknown break date estimates by minimizing the SSR of the OLS regression following Bai and Perron (1998; 2003) methodology. They further prove that when SSR method is used, the test statistics converge to their limiting distributions even for short or bounded series.

The form of breaks are perceieved as sharp breaks, as exercised by the studies above, or smooth breaks. In the literature, smooth breaks are either approximated by exponential/logarithmic smooth transition models (Leybourne et al., 1996; Sollis, 2004) or by Fourier components (Becker et al., 2006; Enders and Lee, 2012a). Application with Fourier components is attractive as testing the significance of Fourier parameters is easier. Fourier Approximation usually introduces one sine term to account for the amplitude and one cosine term for the width of the transitions, determining the coefficients of the terms as the ones minimizing SSR. Enders and Lee updates their test statistic in a consecutive paper claiming DF test statistic has more power compared to LM statistic in the case of absence of a linear trend (Enders and Lee, 2012b). It is known that when fractional Fourier frequencies are used, deterministic part of the time series model can be explained better (Omay, 2015). However, estimation of optimal fractional frequencies takes time and the efficiency gain is not significant.

Another crucial question about the long memory behavior of energy variables is whether the series show the same level of persistence in response to small shocks and big shocks or negative shocks and positive shocks. Previous studies show that shocks have different persistence responses spanning the entire distribution of a time series. We claim that shocks to clean energy series of different size and direction, result in distinct persistence patterns. QUR Test of Koenker and Xiao (2004) addresses these distributional properties allowing to estimate persistence for any distinct quantile.

The QUR methodology starts with the ADF regression with p lags:

$$y_t = \gamma + \beta t + \alpha y_{t-1} + \sum_{i=1}^{p} \phi_i \Delta y_{t-i} + \varepsilon_t \tag{3.3.3}$$

The quantile unit root testing procedure is as follows.
Equation for the null hypothesis is:

$$Q_{y_t}\left(y_t | y_{t-1}, \dots, y_{t-q}\right) = \gamma(\tau) + \theta(\tau)t + y_{t-1} + \sum_{i=1}^{q-1} \phi_i(\tau)\Delta y_{t-i} + \varepsilon_t \tag{3.3.4}$$

where $\tau \in \mathcal{T}$. The null hypothesis is y_t has unit root.

Quantile regression in 3.4 is estimated as follows:

$$Q_{y_t}(\tau | \mathcal{F}_{t-1}) = x_t{}'\beta(\tau) \tag{3.3.5}$$

Minimizes the residuals weighted by the quantile check function:

$$\min_{\alpha \in R^2} \sum_{t=1}^{n} \rho_\tau \left(y_t - x_t'\beta(\tau)\right) \tag{3.3.6}$$

where $\rho_\tau(u) = u(\tau - I(u < 0))$ is the quantile check function.

Equation for the alternative hypothesis is:

$$Q_{y_t}(y_t | y_{t-1}, \dots, y_{t-q}) = \gamma(\tau) + \theta(\tau)t + \alpha(\tau)y_{t-1} + \sum_{i=1}^{q-1} \phi_i(\tau)\Delta y_{t-i} + \varepsilon_t \tag{3.3.7}$$

where $\tau \in \mathcal{T}$ and $\alpha(\tau) \neq 1$. The alternative hypothesis is y_t is stationary.

Then QUR test is performed on y_t, testing if $\hat{\alpha}(\tau) = 1$ or not with the null and alternative hypotheses:

H_0: $\hat{\alpha}(\tau) = 1$

H_{a}: $\hat{\alpha}(\tau) \neq 1$

Like the ADF coefficient t-ratio statistic Koenker and Xiao (2004) use $t_n(\tau)$ for testing. The t-statistic for $\hat{\alpha}(\tau) = 1$ is;

$$t_n(\tau) = \frac{\hat{f}\left(F^{-1}(\tau)\right)}{\sqrt{\tau(1-\tau)}} (y_{-1}^T M_z y_{-1})^{\frac{1}{2}} (\hat{\alpha}(\tau) - 1) \tag{3.3.8}$$

$\hat{f}(.)$: probability density function

$F(.)$: cumulative density function

ε_{-1}: Vector of first lag of $\hat{y}_t$

M_z: projection matrix of $Z = (1, \Delta y_{t-1}, \Delta y_{t-2}, \dots, \Delta y_{t-q+1})$

While working with a specific quantile, a fixed τ, the statistic $t_n(\tau)$ becomes the quantile regression counterpart of the ADF t-statistic (Koenker and Xiao, 2004).

For a complete inference of the unit root process, Koenker and Xiao (2004) suggest examining the process over a range of quantiles, instead of one specific quantile. For this purpose, they use Quantile Kolmogorov-Smirnov (QKS) test statistic for multiple $\tau \epsilon \mathcal{T} = [\tau_0, 1 - \tau_0]$. In this setup, $t_n(\tau)$ is calculated for all $\tau \epsilon \mathcal{T}$, and a maximum over all quantiles is taken as QKS_t.

$$QKS_t = sup_{\tau \epsilon \mathcal{T}} |t_n(\tau)| \tag{3.3.9}$$

The critical values for t-statistics and $\mathrm{QKS_t}$ statistics are obtained both from Hansen (1995) critical values and from the estimations by resampling (bootstrap), and then compared. The limiting distribution of $t_n(\tau)$, which consists of a Dickey-Fuller (DF) component and a standard normal component, is the same as the limiting distribution of Covariate Augmented DF (CADF) Test of Hansen (1995).

$$\delta\left(\int_0^1 \underline{W_1}^2\right)^{-\frac{1}{2}}\int_0^1 \underline{W_1}dW_1+\sqrt{1-\delta^2}N(0,1) \qquad (3.3.10)$$

where δ is the long-run correlation coefficient between ω and ψ from the QR optimization problem in equation 3.3.6 and W_1 is standard Brownian motion. ω and ψ are defined as; $\omega_t = \Delta y_t \; and \; \psi_\tau(u) = \tau - I(u < 0)$. Critical values corresponding to the estimated δ^2 are calculated by fitting a polynomial to the given table of critical values in Hansen's (1995) paper, page 1155. [4]

$$\delta^2 = \hat{\sigma}^2_{\omega,\psi}(\tau)/[\tau(1-\tau)\hat{\sigma}^2_{\omega}(\tau)] \qquad (3.3.11)$$

It is essential to note that QUR should always be complemented with resampling techniques to address issues arising from non-normality and small-sized data. It is well known that the distribution with small samples is skewed left. Furthermore, for unit root or near unit root processes, QUR test statistics exhibit non-standard distributions. In such cases, resampling (bootstrap) can improve the reliability and robustness of statistical estimations (Koenker and Xiao, 2004; Fallahi, 2020). The bootstrap procedure of Koenker and Xiao (2004) that is demonstrated below is explained in detail on p. 8 of their work.

1) They fit the following q-th order autoregression by OLS where $\omega_t = \Delta y_t$.

   $$\omega_t = \sum_{j=1}^{q} \widehat{\beta_j}\omega_{t-j} + \widehat{u_t}, \qquad t = q+1, \dots, n$$

   And obtain estimates $\widehat{\beta_j}$ and the residuals $\hat{u}_t$.

2) Draw iid variables $\{u_t{}^*\}_{t=q+1}^{n}$ from the centered residuals $\widehat{u_t} - \frac{1}{n-q}\sum_{j=q+1}^{n}\widehat{u_j}$ and generate $\omega_t{}^*$ and $u_t{}^*$ using the fitted autoregression:

   $$\omega_t{}^* = \sum_{j=1}^{q} \widehat{\beta_j}\,\omega^*_{t-j} + u^*_t, \qquad t = q+1, \dots, n$$

   with $\omega_j{}^* = \Delta y_j$ for $j = 1, \dots, q$.

3) Then they generate $y_t{}^*$ under the null restriction of a unit root: $y_t{}^* = y^*_{t-1} + \omega^*_t$ with $y^*_1 = y_1$.

4) Finally, they estimate the following p-th order autoregressive quantile regression $y^*_t = a_0 + a_1 y^*_{t-1} + \sum_{j=1}^{p} a_{j+1}\Delta y^*_{t-j} \; + u_t$.

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[4] A complete table of Hansen's critical values is given on Appendix A.

Denote the estimator of $a_1(\tau)$ by $\hat{a}_1^*(\tau)$. Corresponding to $t_n(\tau)$, they construct

$$t_n^*(\tau) = \frac{f\left(\widehat{F^{-1}(\tau)}\right)}{\sqrt{\tau(1-\tau)}}\left({Y_{-1}^*}^T P_X^* Y_{-1}^*\right)^{\frac{1}{2}}(\hat{\alpha}_1^*(\tau) - 1). \tag{3.3.12}$$

In this procedure y_t^* is generated under the null hypothesis of unit root, which ensures the non-stationarity of the generated sample. Thus the subsequent bootstrap test becomes valid. The limiting null distribution of the test statistic is then approximated by repeating steps 2-4 of the above procedure many times. Let $C_t^*(\tau, \theta)$ be the (100 θ)-th quantiles, ie.:

$$P^*[t_n^*(\tau) \leq C_t^*(\tau, \theta)] = \theta \tag{3.3.13}$$

Then the unit root null will be rejected at $(1 - \theta)$ level if $t_n(\tau) \leq C_t^*(\tau, \theta)$.

The intuition behind QUR is that, for instance, when we perform quantile regression at the 0.8th quantile, QUR optimizes a line that places 80% of the data below this line and 20% above it. Consequently, the coefficients obtained from this line emphasize the influence on the dataset's upper extremes. In an application of the method to renewable energy series, if the realized values of renewable consumption significantly exceed recent observations, this indicates a substantial positive shock. In this context, the highest quantiles represent values considerably above the mean, highlighting the presence of positive shocks. Conversely, the lowest quantiles represent values significantly below the mean, capturing negative shocks. For a better understanding of the quantile regression process, a graphical representation, showing the application of this study's methodology to Japanese share of renewables series, is provided in Appendix A.

The issue of structural breaks in quantile regression is embodied by Qu's (2008) work. Qu (2008) and Oka and Qu (2011) test for multiple unknown structural changes on the conditional quantiles rather than conditional mean with a method motivated by BP Test. According to their study the conditional quantile function is linear in parameters and affected by m structural changes.

The setup for QAR is as follows:

$$Q_{y_t}(y_t|y_{t-1}, \dots, y_{t-q}) = Q_u(\tau) + \alpha(\tau)y_{t-1} + \textstyle\sum_{i=1}^{q-1} \phi_i(\tau)\Delta y_{t-i} \tag{3.3.14}$$

$$Q_{y_t}(\tau|\mathrm{x}_i) = \begin{cases} x_t{}'\beta_1(\tau), & t = 1, \dots, T_1^0 \\ x_t{}'\beta_2(\tau), & t = T_1^0 + 1, \dots, T_2^0 \\ \vdots & \\ x_t{}'\beta_{m+1}(\tau), & t = T_m^0 + 1, \dots, T \end{cases} \tag{3.3.15}$$

where $\tau \in (0,1)$ and $\beta_j(\tau)$ $(j = 1, \dots, m+1)$.[5]

In the absence of structural changes one needs to minimize the residuals weighted by the quantile check function as in 3.6:

$$\min_{\alpha \in R^2} \textstyle\sum_{t=1}^{n} \rho_\tau\,(y_t - x_t'\beta(\tau)) \tag{3.3.6}$$

When breaks in a certain quantile is allowed, one needs to minimize 3.16 instead of 3.6:

$$S_T(\tau, \beta(\tau), T^b) = \textstyle\sum_{j=0}^{m} \sum_{t=T_j+1}^{T_{j+1}} \rho_\tau(y_t - x_t'\beta_{j+1}(\tau)) \tag{3.3.16}$$

where $T_0 = 0$ and $T_{m+1} = T$. Then,

$$(\hat{\beta}(\tau), \hat{T}^b) = arg \min_{\beta(\tau), T^b \in \Lambda_\varepsilon} S_T(\tau, \beta(\tau), T^b) \tag{3.3.17}$$

They search for all permissible partitions to find the break dates that achieve the global minimum. Λ_ε is the set of permissible partitions. Then, they perform SQ test to find the structural changes in a particular quantile and DQ test for the structural changes for the quantiles in an interval.

SQ Test statistic:

$$SQ_\tau = sup_{\lambda \epsilon [0,1]} \left\| (\tau(1-\tau))^{-1/2} \left[H_{\lambda,n}\left(\hat{\beta}(\tau)\right) - \lambda H_{1,n}\left(\hat{\beta}(\tau)\right) \right] \right\|_\infty \tag{3.3.18}$$

The test for structural breaks is done using a sub-gradient of the sample where $\lambda \epsilon [0,1]$ is a fraction of the full sample. The statement

$$H_{\lambda,n}\left(\hat{\beta}(\tau)\right) = (X'X)^{-1/2} \; \textstyle\sum_{i=1}^{[\lambda n]} x_i\, \rho_\tau(y_i - x_i'\hat{\beta}(\tau)) \tag{3.3.19}$$

is the same with full sample if there is no structural break in the subsample. Then, when we use $\hat{\beta}(\tau)$ as estimated by the full sample and use it in $H_{\lambda,n}\left(\hat{\beta}(\tau)\right)$, the estimation converges, otherwise it diverges making the SQ test statistic very large.

---

[5] A subset of $\beta_j(\tau)$ may be held constant for the set of regressors that are not subject to any changes.

DQ Test statistic:

$$DQ_{\tau} = sup_{\tau \in \mathcal{T}_{\omega}} sup_{\lambda \epsilon [0,1]} \left\| H_{\lambda,n}\left(\hat{\beta}(\tau)\right) - \lambda H_{1,n}\left(\hat{\beta}(\tau)\right) \right\|_{\infty} \quad (3.3.20)$$

where $\mathcal{T}_{\omega}$ is a closed set consisting of the quantiles of interest.

Oka and Qu (2011) also perform sequential tests for l vs $l+1$ breaks. They offer a testing approach where, one should start by DQ test, then sequential DQ test to determine initial break date estimates. The procedure should follow testing by SQ test then sequential SQ test.

The significance of explaining the deterministic part of a time series is stressed by many authors. According to Box and Tiao (1975), “outlying events can be separated from the noise function and be modeled as changes or interventions in the deterministic part of the general time series model.” Perron (1989) also advises detrending the series according to the existence of structural breaks before analyzing the remaining noise. A strand of the previous studies that allow for structural changes in the application of QUR also involves detrending the data. Bahmani Oskoee and Wu (2018) study portrays one of the mostly applied frameworks in this strand. They regress the series y_t on the deterministic variables.

$$y_t = \alpha + \beta T + \sum_{l=1}^{m+1} \theta_l DU_{l,t} + \sum_{l=1}^{m+1} \rho_l DT_{l,t} + \sum_{k=1}^{n} \lambda_k \sin\left(\frac{2\pi kt}{T}\right) + \sum_{k=1}^{n} \gamma_k \cos\left(\frac{2\pi kt}{T}\right) + \varepsilon_t \quad (3.3.21)$$

where

$DU_{l,t} = 1\ if\ TB_{l-1} < t < TB_l, 0\ otherwise$

$DT_{l,t} = t - TB_{l-1}\ if\ TB_{l-1} < t < TB_l, 0\ otherwise$

$\sum_{k=1}^{n} \lambda_k \sin\left(\frac{2\pi kt}{T}\right)$ and $\sum_{k=1}^{n} \gamma_k \cos\left(\frac{2\pi kt}{T}\right)$ are the Fourier terms and $n = 1$.

In equation 3.3.21, sharp breaks are represented by the dummies $DU_{l,t}$ and $DT_{l,t}$, and smooth breaks are represented by the Fourier terms. They look for optimal k and m, minimizing the SSR of 3.21. Then they detrend the series taking residuals, ε_t, of 3.21, removing the terms for the constant, time trend and sharp and smooth structural changes. Consequently, they apply QUR as stated in Koenker and Xiao (2004) on the residuals.

$$Q_\tau(\hat{\varepsilon}_t|\hat{\varepsilon}_{t-1},\dots,\hat{\varepsilon}_{t-q}) = \alpha(\tau)\hat{\varepsilon}_{t-1} + \alpha(\tau) + \sum_{i=1}^{q-1}\phi_i(\tau)\Delta\hat{\varepsilon}_{t-i}\,;\ \tau \in (0,1) \qquad (3.3.22)$$

The underlying idea here is that the residuals, obtained after removing the deterministic component, contain all of the persistence information of the original series. We accept that working with residuals allows for an approximation to the actual process and provides ease of application. However, by detrending as in here, we assume we have explained everything, and the remaining part is only an AR process with a constant. If the detrending method was inappropriate and could not account for the true structure of the deterministic part, estimated parameter values may be misleading. Thus, we will not be able to get intuitive persistence parameter estimates. Genuine long-term trends may be removed with detrending, obscuring their association with the underlying economic process, resulting in inexplicable AR coefficients for some datasets even.

It is worth reminding that each structural break may have a distinct impact on various quantiles (Qu, 2008; Oka and Qu, 2011). Some break parameters may exhibit higher or lower values for specific quantiles, thereby influencing the persistence parameter differently for individual quantiles. Therefore, endogenizing the structural change parameters in the QUR process allows for more intuitive and informative persistence estimation.

We modified Koenker and Xiao's QUR by endogenizing the parameters for sharp and smooth structural changes. We try to build a comprehensive version of the BP (2003) structural break test. This version allows for the inclusion of smooth break terms along with sharp trend and intercept break components within the optimization process. Our approach to determining breaks follows a two-step process: Firstly, we identify the break dates minimizing the SSR of the model that allows for the estimation of sharp and smooth structural breaks simultaneously. Subsequently, we test for the significance of sharp break dates by applying the BP test. The two-step procedure uses Fourier frequencies and sharp break dummies.

Step 1: Simultaneous detection of sharp break dates and Fourier smooth break terms by minimizing the SSR of the following base model:

$$y_t = \gamma + \beta t + \alpha y_{t-1} + + \sum_{i=1}^{\rho} \lambda_i \Delta y_{t-i} + \sum_{l=1}^{m+1} \theta_l DU_{l,t} + \sum_{l=1}^{m+1} \mu_l DT_{l,t} + \sum_{k=1}^{n} \varphi_k \sin\left(\frac{2\pi kt}{T}\right) + \sum_{k=1}^{n} \phi_k \cos\left(\frac{2\pi kt}{T}\right) + \varepsilon_t \quad (3.3.23)$$

$DU_{l,t} = 1\ if\ TB_l \leq t < TB_{l+1},\ 0\ otherwise$

$DT_{l,t} = t - TB_l\ if\ TB_l \leq t < TB_{l+1},\ 0\ otherwise$

$n = 3$

k: $Fractional\ Fourier\ Frequency$

m: $number\ of\ structural\ breaks$

ρ: $number\ of\ lagged\ differences$

TB: $Time\ of\ break$

Number of lagged differences is determined by Shwarz's Bayesian Information Criteria (SBIC).

Step 2: Testing for the sharp break dates by Bai and Perron (1998, 2003) test

$$y_t = x_t{}'\Psi + z_t{}'\Phi + \varepsilon_t \quad (3.3.24)$$

x: vector of non-shifting variables

z: vector of shifting variables

Obtain m, T_i, Ψ and Φ minimizing the SSR:

$$\sum_{i=1}^{m+1} \sum_{t=T_i-1}^{T_i} [y_t - x_t{}'\Psi - z_t{}'\Phi]^2 \quad (3.3.25)$$

"x" comprises of first lag and the lagged differences of dependent variable, also, the Fourier terms obtained from the first step.

We assume that the estimated model is linear in parameters. Carrion-i Silvestre and Gadea (2015) addresses the issue of determining the maximum number of breaks allowed by minimizing Bayesian Information Criteria (BIC). We may have used BIC as well but we decided to allow for at most 3 sharp breaks in our procedure because the number of observations in the annual clean energy series is low. Allowing for too many breaks will lead to overparameterization and decrease degrees of freedom. Also, we experienced that allowing for more than 3 breaks has made the estimation procedure cumbersome. Thus, we need to allow for the lowest possible number of breaks. Allowing for 1 or 2 breaks is a common choice for most of the unit root tests with structural breaks.

However, when we consider the events affecting the energy series in our timeline and observe the country series, 1 or 2 breaks, may not capture the whole picture. We may even face misspecification problems. As you will see in Tables 3.4.3 and 3.4.4, two mostly used unit root tests with structural breaks, ZA and LS, could not determine some known breaks correctly. When we tried 3 breaks option, we found break dates that are corresponding to significant country-specific events. Thus, we settle for 3 breaks.

Methodology in Step 1 involves introducing the break dates as dummy variables and smooth break terms in Fourier form in a linear regression setup. Then the optimal break dates and Fourier Frequencies are determined by minimizing the SSR. BP Test in Step 2 uses the Fourier frequencies from the 1st step as non-shifting parameters and estimates the break dates by partitioning the linear regression equation with shifting parameters into an optimal number. Both procedures eventually determine the break dates by SSR minimization. Even if the procedures used in the two steps are not identical, sharp break dates obtained by the 1st and the 2nd step are consistent. That is why smooth break terms obtained in the first step are considered admissible to use in the vector of non-shifting parameters in the BP Test and the resulting regression equation for the unit root test. The break detection procedure allows for objectively estimating the break dates and Fourier frequencies by a data-dependent method. When the appropriate break dates and frequencies are obtained, we set the regression equation for quantiles in the alternative hypothesis of the Quantile Unit Root Test. Our QUR testing procedure is as follows. The main difference from the original QUR is the alternative hypothesis.

Equation for the null hypothesis: y_t is a unit root process without breaks

$$Q_{y_t}\left(y_t | y_{t-1}, \dots, y_{t-q}\right) = \gamma(\tau) + \beta(\tau)t + \alpha(\tau)y_{t-1} + \sum_{i=1}^{q-1} \phi_i(\tau)\Delta y_{t-i} \qquad (3.3.26)$$

where $\tau \in [0.1, 0.2, \dots, 0.9]$ and $\alpha(\tau) = 1$.

Equation for the alternative hypothesis:

$$Q_{y_t}\left(y_t|y_{t-1},\dots,y_{t-q}\right)=\gamma(\tau)+\beta(\tau)t+\alpha(\tau)y_{t-1}+\sum_{i=1}^{q-1}\phi_i(\tau)\Delta y_{t-i}+\sum_{l=1}^{m+1}\theta_l(\tau)DU_{l,t}+\sum_{l=1}^{m+1}\mu_l(\tau)DT_{l,t}+\sum_{k=1}^{n}\varphi_k(\tau)\sin\left(\frac{2\pi kt}{T}\right)+\sum_{k=1}^{n}\lambda_k(\tau)\cos\left(\frac{2\pi kt}{T}\right)+\varepsilon_t \quad (3.3.27)$$

Then we test if $\hat{\alpha}(\tau)=1$ or not with the null and alternative hypotheses.

Since we are working with specific quantiles, a fixed τ, we use the quantile regression counterpart of the ADF t-statistic as $t_n(\tau)$. Then, we use Quantile Kolmogorov-Smirnov (QKS) test statistic for multiple $\tau\epsilon\mathcal{T}=[\tau_0,1-\tau_0]$. In this setup, $t_n(\tau)$ is calculated for all $\tau\epsilon\mathcal{T}$, $\mathcal{T}=(0.1,0.2,\dots,0.9)$ in our case, and a maximum over all quantiles is taken as QKS_t. The critical values for t-statistics and QKS_t statistics are obtained both from Hansen (1995) critical values and from our estimations by resampling (bootstrap) with 1000 replications.

We study the asymmetric persistence behavior of share of renewables and share of nuclear energy series affected by the sharp and smooth structural changes. In order to do that we look for the sum of AR coefficients as the persistence measure for each quantile. Then, compare the magnitude of the coefficient of first lag with the one found in the ADF regression and with the coefficients found in the regression of every other quantile. Then we are able to see the persistence impact of small or big shocks and negative or positive shocks.

As for most of the unit root tests with structural breaks, it should be emphasized that we do not view our test as a substitute for the QUR test but as an auxiliary test that is appropriate when the analyst has reasons to suspect the possibility of structural change.

3.4. Empirical Results

3.4.1. Preliminary Unit Root Test Results

The conventional unit root tests, such as the Augmented Dickey-Fuller (ADF) and Kwiatkowski-Phillips-Schmidt-Shin (KPSS) tests, have been conducted on the shares series to assess their stationarity properties. Results are shown in Table 3.4.1. The ADF test does not reject the null hypothesis of a unit root at any level, indicating that the series are non-stationary. Similarly, the KPSS test rejects the null hypothesis of stationarity for all countries, further supporting the conclusion that the series are non-stationary. These results suggest that the shares series do not exhibit fractional integration.

Table 3.4.1 Conventional Unit Root Tests for Level Series: Share of Renewables and Share of Nuclear Energy

Share of Renewables

	China	**US**	**France**	**Brazil**	**Germany**	**Japan**	**UK**
ADF							
Lags	0	0	1	0	0	0	0
Has a unit root with Trend and Intercept	9.2	-0.331	3.862	-1.22	5.86	0.914	10.74
KPSS							
Stationary with Trend and Intercept	0.209**	0.190**	0.177**	0.140*	1.37***	0.238***	0.213**

Share of Nuclear Energy

	China	**US**	**France**	**Brazil**	**Germany**	**Japan**	**UK**
ADF							
Lags	0	0	3	0	0	1	0
Has a unit root with Trend and Intercept	3.691	-0.763	-2.118	-2.681	1.007	-1.035	-0.368
KPSS							
Stationary with Trend and Intercept	0.253***	0.157**	0.139*	0.168**	0.190**	0.184**	0.211**

Lag length is determined by Shwarz's Bayesian Information Criteria (SBIC)

Reject the null hypothesis with: *** $p<0.01$, ** $p<0.05$, * $p<0.1$

Reject the null hypothesis with: *** LM>0.01 critical value, ** LM>0.05 critical value, *LM>0.1 critical value

When structural breaks are not considered the level series of select (renewable energy consumption share) and snuclear (nuclear energy consumption share) show evidence of having unit roots. These results shed light on the potential persistence characteristics of the shares series and provide a basis for further analysis. In this study, three preliminary unit root tests with structural breaks are used: For determining sharp breaks: Zivot-Adrews (henceforth ZA) (1992), Lee-Strazicich (henceforth LS) (2003, 2004) tests, for smooth breaks: Enders-Lee (henceforth EL) (2012) test.

The consideration of structural breaks in the analysis can lead to different results compared to the conventional unit root tests. Tables 3.4.2 and 3.4.3 show that the LS test supports the claim that the inclusion of structural breaks can result in stationarity for variables that are otherwise non-stationary. Most of the series in the study exhibit stationarity after accounting for structural breaks using the LS test, except for Japan in the share of renewables and France, Germany, and the UK in the share of nuclear series.

It is worth noting that the ZA and EL tests did not yield stationarity results in this analysis. The failure of the ZA test could be attributed to its limitation of allowing only one break, while many country series exhibit multiple breaks. Additionally, one-break tests may not accurately predict the exact break date, as the presence of other overseen breaks can affect the underlying model.

Smooth break tests, on the other hand, may result in stationary series by providing a good fit to the original series without the need to precisely determine the break date. However, in the energy series under consideration, the unit root null hypothesis cannot be rejected even with the EL test. This is because the series cannot be fully explained by smooth breaks alone, as there are sharp breaks associated with sudden capacity gains, global events, policy interventions, technical accidents, or natural disasters, which are evident in the graphs presented in Figures 3.2.6 and 3.2.7.

Determining the exact break dates is often challenging, as it is not always easy to differentiate between two candidate dates based on visual inspection alone. Country-specific events and considerations are necessary for identifying break dates, but even then, multiple events can be associated with different candidate break dates identified by different tests. Therefore, it is important to exercise caution when interpreting the results of the tests, particularly when known break dates are not identified by the tests.

It should be noted that the break dates determined by the ZA and LS tests do not match each other in any case. This discrepancy is expected due to the differing setups of these tests: the null hypothesis in the ZA test does not account for breaks, whereas it assumes breaks in the LS test. It is indeed an important observation that the estimated break dates from the ZA and LS tests do not match the known shocks to the series as well. We have mentioned before that ZA allows for only one break which may not be able to explain the whole series. Furthermore, LS allows for two breaks but does not consider smooth breaks, which may cause problems in estimating the break dates. For example, in the case of Japan's share of renewables and share of nuclear energy series, the Fukushima Disaster in 2011 is a significant event that should ideally be captured as a break date. Similarly, the 1970s' Oil Crisis had a notable impact on nuclear energy shares for several countries. However, Table 3.4.2 and 3.4.3 show that neither the ZA test nor the LS test accurately determines these known break dates.

The inconsistency between estimated break dates and dates of certain events that cause shocks, can lead to challenges in achieving stationarity after accounting for structural breaks. The misspecification of breaks could be a contributing factor to the failure to reach stationarity. As a result, alternative methods for determining break dates need to be considered to capture the true nature of structural changes in the series accurately. It is crucial to address this issue and employ techniques that can provide more precise and reliable break date identification. By using other methods, that can detect both sharp and smooth breaks we can better capture the actual structural changes in the series and improve the analysis of persistence and stationarity.

3.4.2. Country-Specific Analysis of Sharp and Smooth Breaks

In the process of determining sharp break dates and smooth break frequencies, the BP multiple structural break test is modified by incorporating both intercept and trend dummies for sharp breaks and Fourier Frequency terms for smooth breaks. By simultaneously evaluating various combinations of break dates and Fourier Frequencies, the model aims to identify the configuration that results in the lowest Sum of Squared Residuals. This involves considering all possible sharp intercept and trend break dates up to 3 breaks and exploring Fourier Frequencies between 1 and 5,

Table 3.4.2 Unit Root Tests with Structural Breaks for Share of Renewable Energy

Share of Renewables							
	China	**US**	**France**	**Brazil**	**Germany**	**Japan**	**UK**
Zivot and Andrews (1992)							
Null Hypothesis	Break Dates and t-Statistic						
Has a unit root without breaks	2009: -2.802	2000: -5.44**	2009: -2.943	1977: -2.730	2001: -1.624	2009: -1.525	2008: -1.266
Lee and Strazicich (2003, 2004)							
Null Hypothesis	Break Dates and LM-Statistic						
Has a Unit Root wt at most 1 break in intercept and trend	2005: -4.860***	2008: -4.233***	2005: -1.773	1991: -2.512	1999: -3.169	2002: -2.03	2005: -3.906**
Has a Unit Root wt at most 2 breaks in intercept and trend	1999 & 2008: -5.062***	1997 & 2010: -4.814**	1962 & 2008: -4.032*	1981 & 1998: -4.043*	1997 & 2007: -5.477***	1966 & 2006: -3.855	1996 & 2008: -6.907***
Enders and Lee (2012)							
Null Hypothesis	Fourier Frequency and LM-Statistic						
Has a Unit Root wt Fourier smooth breaks	1: -2.298	1: -2.669	1: -2.498	2: -1.861	1: -0.334	1: -2.034	1: -0.567

Lag length is determined by t-statistic significance.
Reject the null hypothesis with: *** p<0.01, ** p<0.05, * p<0.1
Reject the null hypothesis with: *** LM>0.01 critical value, ** LM>0.05 critical value, *LM>0.1 critical value

Table 3.4.3 Unit Root Tests with Structural Breaks for Share of Nuclear Energy

Share of Nuclear							
	China	**US**	**France**	**Brazil**	**Germany**	**Japan**	**UK**
Zivot and Andrews (1992)							
Null Hypothesis	Break Dates and t-Statistic						
Has a unit root without breaks	2009: -2.802	1985: -2.849	1980: -4.576	2001: -7.856	1984: -3.082	2004: -3.482	1992: -4.375
Lee and Strazicich (2003, 2004)							
Null Hypothesis	Break Dates and LM-Statistic						
Has a Unit Root wt at most 1 break in intercept and trend	1993: -3.534*	1983: -2.187	1992: -1.777	1999: -4.410***	1991: -1.808	1996: -2.625	1993: -3.463*
Has a Unit Root wt at most 2 breaks in intercept and trend	1992 & 2010: -6.749***	1966 & 1988: -5.641***	1971 & 1988: -3.207	1999 & 2005: -7.599***	1965 & 1991: -2.269	1983 & 2009: -4.446**	1987 &2004: -3.514
Enders and Lee (2012)							
Null Hypothesis	Fourier Frequency and LM-Statistic						
Has a Unit Root wt Fourier smooth breaks	1: -3.125	1: -2.547	1: -3.496	1: -3.519	1: -2.563	1: -2.851	1: -3.115

Lag length is determined by t-statistic significance.
Reject the null hypothesis with: *** $p<0.01$, ** $p<0.05$, * $p<0.1$
Reject the null hypothesis with: *** LM>0.01 critical value, ** LM>0.05 critical value, *LM>0.1 critical value

with 1-point increments. This approach allows for a comprehensive analysis of the data, taking into account both sharp and smooth breaks to explain the clean energy shares series of the energy sector.

Table 3.4.4 BP Test for Structural Breaks for Share of Renewable Energy

Bai and Perron (1998, 2003)

	China	**US**	**France**	**Brazil**	**Germany**	**Japan**	**UK**
Specs	Break Dates and Scaled F-Statistics						
Breaks in intercept	2003:	2000:	2009:	1990:	1994, 2002, 2011:	1960, 2010:	2008:
and trend	39.209***	35.153***	25.312***	19.320***	21.259**	18.037**	13. 327**
Breaks in intercept	2003, 2011:	2000:	2005, 2015:	1975, 2002:	1995, 2003, 2011:	1960, 2011:	2010:
and trend/	30.212***	37.752***	14.03**	14.354**	24.865***	14.069**	18.543***
Fourrier Freq	FF: 1	FF: 5	FF: 5	FF: 1	FF: 3	FF: 3	FF: 1

Lag length is determined by Shwarz's Bayesian Information Criteria (SBIC).
Break date significance with: *** F-stat>0.01 CV, ** F-stat >0.05 CV, * F-stat >0.1 CV.
Break dates are determined with 10% trimming. and tested at 5% significance level.

Table 3.4.5 BP Test for Structural Breaks for Share of Nuclear Energy

Bai and Perron (1998, 2003)

	China	**US**	**France**	**Brazil**	**Germany**	**Japan**	**UK**
Specs	Break Dates and Scaled F-Statistics						
Breaks in intercept	1994, 2011:	1973, 1988:	1980:	1984, 2001:	1984:	1978, 2003, 2011:	1993, 2009:
and trend	38.967***	18. 478***	44.172***	22.436***	36.061***	18.373**	18.098***
Breaks in intercept	1994, 2003, 2013:	1998:	1977, 1989:	1984, 1993, 2001:	1984, 2011:	2011:	1992, 2009:
and trend/	61.833***	31.909***	15.932***	29.931***	32.072***	104.696***	26.896***
Fourier Freq	FF: 5	FF:2	FF: 1	FF: 3	FF: 1	FF: 2	FF: 4

Lag length is determined by Shwarz's Bayesian Information Criteria (SBIC).

Break date significance with: *** F-stat>0.01 CV, ** F-stat >0.05 CV, * F-stat >0.1 CV.

Break dates are determined with 10% trimming.

Table 3.4.4 and Table 3.4.5 shows estimated BP break dates. The first line exhibits the estimations only with sharp breaks and the second line exhibits the estimations with both sharp and smooth breaks. We then model each series with sharp and smooth breaks, as well as considering the lagged terms determined by SBIC.

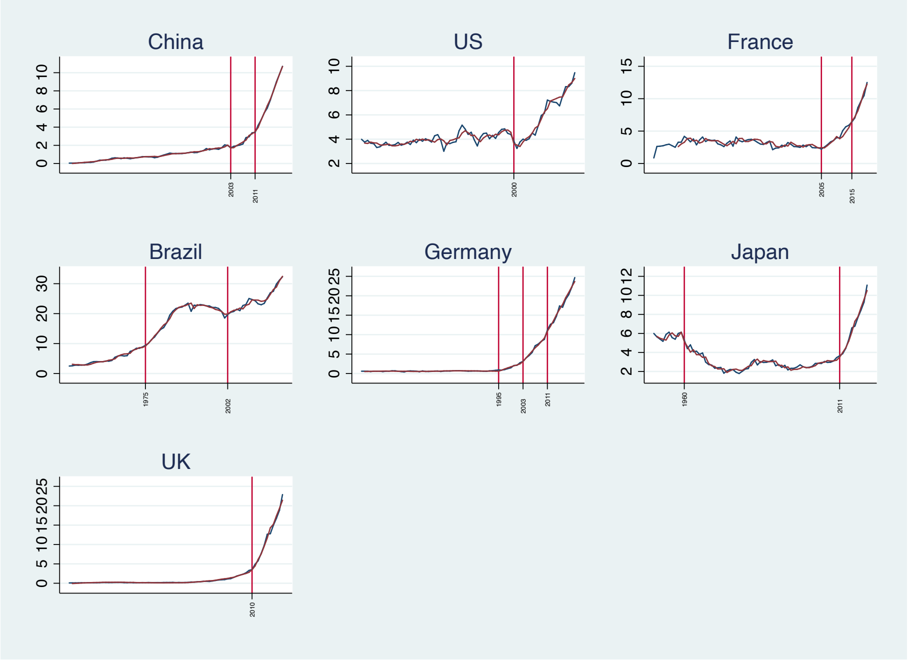

Figure 3.4.1 Sharp and Smooth Breaks by Countries: Share of Renewables in Primary Energy Consumption (%)

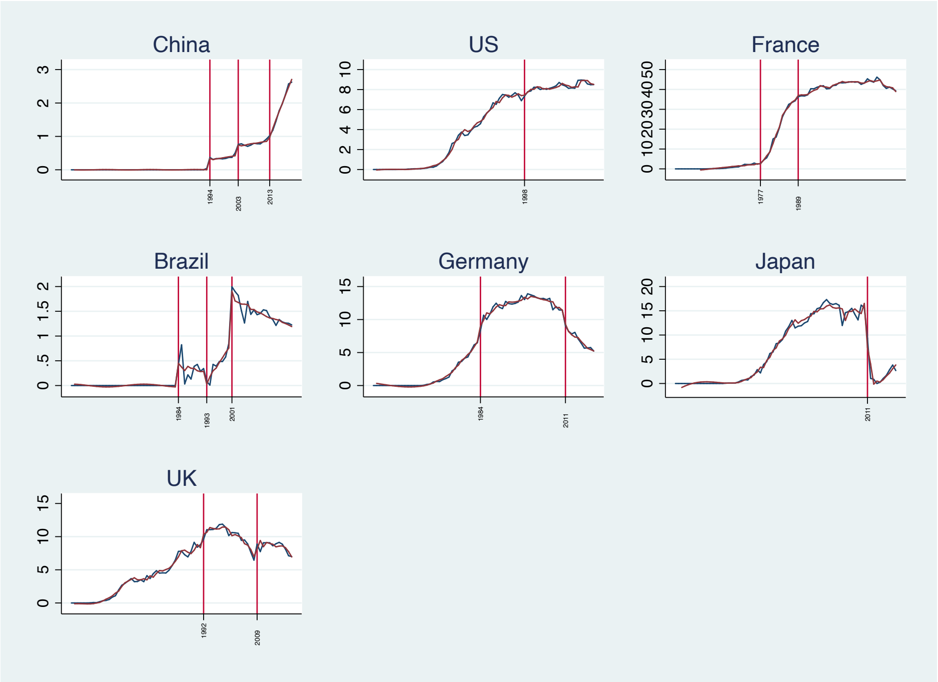

Figure 3.4.2 Sharp and Smooth Breaks by Countries: Share of Nuclear in Primary Energy Consumption (%)

As mentioned by Carrion-i Silvestre et al (2005; 2015) and Kim and Perron (2009), the use of the BP test for multiple structural breaks seems to provide more accurate break date identification compared to the previous ZA and LS tests. The break dates determined by the BP test align more closely with the graphical representations in Figures 3.2.6 and 3.2.7, as well as with the candidate events for breaks. Notably, the BP test successfully identified the 2011 Fukushima Disaster for Japan and Germany, the 2000 California electricity crisis in the US, and the 1970s' Oil Crisis that led to an increase in nuclear energy consumption in US, France, and Japan.

Furthermore, the introduction of smooth break terms with Fourier Frequencies improved the precision of sharp break dates. By properly accounting for the smooth parts of the series, the sharp break dates could be detected more accurately. For instance, in the share of renewables series for Japan, the inclusion of smooth breaks allowed for the detection of 2011 as a break date instead of 2010. The nature of the energy sector, as discussed in the Literature Review part, suggests that smooth breaks also play a significant role. By incorporating smooth break terms, the analysis becomes more comprehensive and enables a more precise identification of break dates. Figures 3.4.1 and 3.4.2 shows the modeled predictions of the series for share of renewables and share of nuclear energy respectively, with estimated break dates emphasized.

China

In the share of renewable energy series, the break date of 2003 aligns with the structural change in the Chinese economy. As China's economy entered a rapid growth phase in the early 2000s, the energy demand of the industrial sector increased. The signing of the Kyoto Protocol in 2002 further pushed the development of the renewable energy sector. The 2003 break in renewable energy consumption reflects this structural change in the economy. The break date of 2011 may not be directly related to the Fukushima disaster, as nuclear energy shares did not decrease. However, the Fukushima disaster may have accelerated the consumption of renewable energy in China, as the country became more cautious about nuclear energy. The release of the Chinese government's 12th Five Year Plan in 2011, which promoted clean energy, including hydropower and nuclear power, further contributed to the increase in renewable energy consumption from 2011 onwards.

In the share of the nuclear energy series, the first two break dates in China correspond to the commercial operation dates of the first wave reactors (Daya Bay and Qinshan-I) in 1994 and the second wave reactors (Ling Ao and Qinshan-II&III) in 2003. There is a gradual increase starting from 2007 with the beginning of the third wave reactors period. However, the increase in 2007 is not significant compared to the following years, which is why it may not have been detected as a break date. The third wave of reactors continued at a slow pace, especially after the Fukushima disaster. Although we see a rapid increase in renewable energy consumption following 2011, we do not observe a similar increase in nuclear energy consumption. This can be attributed to the impact of the Fukushima disaster. Shortly after Fukushima, the State Council of China decided to suspend approvals for new nuclear power plants.

However, as a country heavily dependent on industrial production, China could not completely abandon nuclear energy. The approval of the "12th 5-year Plan for Nuclear Safety and Radioactive Pollution Prevention and Vision for 2020" in 2011 marked a recommitment to nuclear energy. Starting in 2013, the operation of third-wave reactors accelerated, adding significant capacity in subsequent years.

The inclusion of smooth break terms in the modeling of the series has helped detect the break dates more accurately for China. The 2011 break in the share of renewable energy series aligns with significant events and policy changes, providing evidence for a structural change. The more evident break date of 2003 in the share of nuclear energy series could not be detected without the inclusion of smooth breaks, highlighting the importance of considering both sharp and smooth breaks in the analysis.

US

The year 2000 marked an important event for the energy sector with OPEC members deciding to cut oil production quotas. This decision had implications worldwide and led to the 2000-2001 California electricity crisis, caused by delays in the approval of new power plants. The economic fallout from this crisis spread beyond California's borders. The share of renewables initially increased due to a decrease in oil consumption. Subsequently, a series of policies promoting renewable energy consumption to reduce dependence on foreign oil resulted in a structural change in the renewable energy sector. The government, faced with an energy crisis, decided to invest more in renewables, leading to a change in the overall energy supply structure since 2000. The development of the National Energy Policy (NEP) in 2001 aimed to promote dependable, affordable, and environmentally sound energy production and distribution.

In the United States, the share of the nuclear energy graph exhibits a smooth structure. The construction of the first nuclear reactor began in 1968, and the country currently has 92 operating nuclear reactors, all of which started commercial operation between 1974 and 1993. The break dates determined without considering smooth breaks, such as 1973 and 1988, are close to the years when the commercial operation of reactors began. The US graph in Figure 3.4.2 provides insights into this story. During the oil crisis, the US chose to prioritize the development of nuclear energy as a replacement for oil. However, after the Three Mile Island accident in 1979, new nuclear reactor construction was halted for a period of time. The subsequent capacity increase can be attributed to the grid connection of ongoing projects.

The break dates without smooth breaks are close to the known events but not exact. However, when smooth break terms are included, the smooth structure of the US curve aligns well with a high Fourier Frequency, and the sharp break dates of 1974 and 1993 become invisible. This observation makes sense because the systematic commercialization of nuclear energy in the US spanned over a period. The country initially started with low-capacity reactors and gradually developed higher-capacity reactors while also improving the capacity of existing reactors. A report from the World Nuclear Association indicates that performance increases in the US nuclear sector began to accelerate in 1998 due to mergers and acquisitions. Under the smooth breaks scenario, the break date of 1998 can be detected. Interestingly, 1998 was also the year when the US signed the Kyoto Protocol. The decline in 1997 is attributed to the shutdown of a reactor with a capacity of around 1000 MWe.

Overall, the inclusion of smooth break terms allows for a better understanding and detection of break dates in the series for both the share of renewables and the share of nuclear energy in the United States. It reveals the underlying patterns and structural changes that are not apparent when considering only sharp breaks.

France

In the case of France, the break dates for the select series are 2005 and 2015, which clearly demonstrate the impact of the Kyoto Protocol and the Paris Agreement. Although France signed the Kyoto Protocol in 1998, policies to promote renewable energy did not immediately emerge. The Kyoto Protocol came into force globally in 2005 after the ratification of Russia and Canada. The Annex I period was from 2008 to 2012, and France’s action plan for its Kyoto commitments was expressed in the “Climate Plan 2004-2012.” Effective policies were implemented following 2005, as indicated by the sharp increase in France’s select series. France accepted the principles of the Kyoto Protocol, developed, and adopted them, and hosted the signing of the Paris Agreement in 2015. In 2014, the French government passed a law worth $13.4 billion, promoting renewable energy sources through tax credits and low-interest loans. Thus, together with the Paris Agreement and the implementation of wind energy promotion policies, another break occurred in 2015.

France has set an ambitious goal of reducing carbon emissions by 75% by 2050, and they are closer to achieving this goal compared to any other country, largely due to their reliance on nuclear energy. After the oil crisis, France installed its first nuclear reactor in 1977 and made significant investments in the sector, reaching a total capacity of 34,900 MWe before 1980. However, by the end of the 1980s, it was realized that nuclear energy capacity and demand were not aligned. This led to a slowdown in investments. In the following years, nuclear energy production did not pick up significantly due to the costly renovations required and concerns about nuclear security. Additionally, the opposition to nuclear energy across Europe had an impact on the ruling governments of the 2000s. In the case of France, the use of smooth breaks is necessary to identify the fitting break dates, both for the select series and the snuclear series. Without considering smooth breaks, the underlying structural changes and their corresponding dates cannot be accurately detected.

Brazil

In the case of Brazil, the smooth transition to renewables during the oil crisis and the swift reaction to the Kyoto Protocol after the economic crisis of 2002 (which is also the sign date for the protocol) are evident on the graph. The period before 2002 shows a smooth structure, with a gradual increase in renewable shares following the 1970s' oil crisis and a smooth decrease in the trend of renewable shares following the grid connection of Brazil's first nuclear reactor. Without considering smooth breaks, it is difficult to predict the exact dates of structural breaks. However, when smooth break terms are added, the major breaks following the oil crisis in 1975 and the pick-up in 2002 with the signing of the Kyoto Protocol can be detected.

Around 20% of Brazil's energy sector depended on renewables in the 2000s but we observe a decline in the renewable consumption along with an increase in nuclear energy consumption in Figure 3.2.5. Decrease in the share of renewables was most probably due to the slowing industrial renewable energy consumption during the economic slowdown in Brazil around 2002 and nuclear energy consumption occupying a larger slice in total primary energy consumption following the grid connection of a major nuclear reactor in 2001. Although the 2008 crisis hit developing countries hard, it was not a significant break date in any of the break tests for Brazil's select series.

The consumption of nuclear energy in Brazil started in 1982-1984, during the grid connection period of its first reactor, Angra I. However, Angra I had to shut down for a period of time in its early years due to problems with its steam supply system. Brazil's military government between 1964 and 1985 was characterized by instability, and the country's equally unstable economy in the 1980s, known as the "lost decade," along with political turmoil until the 1994 presidential election, prevented the full operation of Brazil's only nuclear reactor. The decline in 1993 can be attributed to poor management. We can detect the following year of the grid connection of the second nuclear reactor in 2000 as a break. The reason we cannot see 2000 but we can see 2001 as a break date is likely because 2000 is the grid connection date but 2001 is the commercial operation date. Moreover, the consumption behavior of the sector agents needs some additional time to adapt to the increasing supply of nuclear energy.

Germany

Germany's transition to increased renewable consumption began later compared to other developed countries. The first significant increase in renewable consumption is observed in 1995, just before the Kyoto Protocol. Prior to 1995, Germany had low but stable renewable energy use mainly from hydro power. The period from 1990 to 2010 is known as the "bioenergy boom" in Germany. Although the 1995 break does not coincide with a specific event, it represents the initial increase in the trend of renewable energy shares.

After the Chernobyl accident in 1986, Germany drastically changed its stance on nuclear power. The accident site was in close proximity to the German border, leading to public perception that a radioactive cloud had spread across Northern Germany. The decision to phase out nuclear power was made in 2000, while the country also needed to meet the targets set by the Kyoto Protocol. Share of nuclear energy does not increase after 2000. As an industrial powerhouse, Germany needed to quickly replace nuclear energy to meet its energy demands. The share of renewable energy was already on the rise before the Kyoto Protocol. Following the sign date of the protocol, a break in the select series can be detected in 2003. At this stage, Germany was already in the process of phasing out nuclear power, but the Fukushima Disaster prompted the immediate closure of eight nuclear plants, as voted by the pro-nuclear party-led German parliament. This is why we can observe a break date in Germany's share of renewables graph in 2011.

On Figure 3.4.2, we can observe a sharp increase in Germany's snuclear series in 1984. During this phase of promoting nuclear power in Germany, three new high-capacity nuclear plants were connected to the grid in 1984, significantly increasing nuclear energy consumption. However, we cannot detect 1986 (Chernobyl) as a break date, likely because it is very close to 1984 and falls within the trimming range of the BP (Bai-Perron) process. Until 2011, Germany was already shutting down its nuclear reactors, but after the Fukushima disaster, immediate closure of eight plants was enforced, with all others scheduled to be shut down by 2022. Without considering smooth breaks, we would not be able to detect 2011 as a break date in nuclear shares, despite it being a clear structural break for Germany's nuclear energy sector.

Japan

During the accelerated growth period of the 1960s in Japan, total energy consumption increased while renewable energy sources were abundant. As a result, the share of renewables declined during this period. The changes associated with the Kyoto Protocol and the first commitment period (2008-2012) in Japan were gradual and slow. After signing the treaty in 2002, it took time for policy generation and the realization of the policy targets. Japan's nuclear energy sector was already well-established, which may have contributed to the slower transition to renewable energy (Ohta, 2020). Without considering smooth breaks, a break date of 2010 was detected in select series. The exact date of the sharp break following the Fukushima disaster in 2011 cannot be captured without incorporating smooth breaks.

Incorporating smooth break terms in the snuclear series also helps retain the detection of the sharp break in 2011. However, the inclusion of smooth breaks may make it challenging to accurately model other sharp breaks in the data, as the significant and sharp decline observed in 2011 dominates the overall pattern. If the sample is divided into two parts as 1950-2011 and 2011-2020, it is possible that a break in 1978 corresponding to the oil crisis and a break for the decline in 2003 due to due to a nuclear safety scandal at Tokyo Electric Power Co., could be detected. These events may exhibit distinct patterns that are overshadowed by the sharp break in 2011 when considering the entire sample.

UK

The UK experienced a smooth transition in its renewable energy policies following the first commitment period of the Kyoto Protocol (2008-2012). The implementation of the Climate Change Act in 2008 and the Renewable Energy Act in 2009 were significant steps towards promoting renewable energy production. However, the sharp break in renewable energy consumption is observed around 2010, indicating the implementation year of guaranteed payments and incentives for producers. Regarding the UK's nuclear energy sector, it experienced a period of growth between 1989 and 1995, with the commercial operation of five power stations. The break in 1992 represents this period of expansion. However, in the 2000s, nuclear power became a subject of political debate, considering factors such as cost-benefit analysis and energy safety. In 2002, the government made a decision to halt the construction of new nuclear power stations.

Incorporating smooth break terms in the modeling process is essential to capture the gradual changes in the UK's renewable energy sector and to detect the sharp break in 2010. Similarly, smooth breaks can help analyze the dynamics of the nuclear energy sector, including the growth period in the early 1990s and the subsequent political debate in the 2000s.

UK government provided the green light for investments in nuclear energy in 2008, which led to an increase in nuclear energy consumption in 2009. However, despite this initial increase, the share of nuclear energy did not continue to rise in the following years due to a greater focus on promoting renewable energy sources, particularly in response to climate concerns and the impact of the Fukushima Nuclear Disaster. The shift towards promoting renewables and the hesitation towards nuclear energy expansion can explain the continued decline in nuclear energy shares in the UK. This suggests that the country's energy policy priorities and public sentiment favored renewable energy sources over nuclear power during that period.

3.4.3. Asymmetry in Persistence Characteristics

QUR Test results and related statistics are shown in Tables 3.4.6, 3.4.7, 3.4.8, and 3.4.9. The QUR Test is estimated for all deciles: 1st – 9th quantiles. $\alpha_1(\tau)$ is the sum of AR coefficients for each quantile (coefficient of the first lag of variables select and snuclear in the ADF regression of each country) demonstrated in equations 3.3.7 and 3.3.27. $t_n(\tau)$ is the test statistic for the corresponding quantile estimated by equation

3.3.8 for a fixed τ. α_{OLS} is the sum of AR coefficients of the whole sample OLS regression in equations 3.3.3 and 3.3.23. 10% Hansen (1995) critical values and 10% bootstrap critical values (1000 replications) are also shown. Moreover, we estimate half-lives, which is interpreted as the years required for the decrease of a shock to half of its original value, to have a better understanding of the persistence responses. Half-life is estimated by equation 3.3.2 for each quantile. As suggested by Koenker and Xiao (2004), Hansen critical values are estimated via fitting a polynomial to the given table of critical values in Hansen's (1995) paper, page 1155.[8] We also report QKS statistics estimated by equation 3.3.9 that help analyze the unit root behavior over a range of quantiles.

Figures 3.4.3 and 3.4.4 show the changes in model coefficients across quantiles more clearly. $\alpha_1(\tau)$, sum of AR coefficients is used as a persistence measure. u_t, is the quantile value of the residual. It is interpreted as an approximation to the magnitude of shock corresponding to each quantile. We can see the asymmetric persistence response of each series to negative and positive shocks, as well as small and large shocks by observing u_t and $\alpha_1(\tau)$. Reviewing first segments of Figures 3.4.3 and 3.4.4 for u_t, we can see that u_t is negative in lower quantiles and positive in higher quantiles. Also, it takes a value of zero for the median. The behavior of u_t is consistently related to the logic behind quantile unit root test as u_t represents shocks to the series. By employing the QUR test and examining the changing $\alpha_1(\tau)$ coefficients, we can observe the asymmetry in the persistence behavior of the share of clean energy series in Figures 3.4.3 and 3.4.4. This approach offers a more comprehensive understanding of the stochastic properties of the series compared to conventional OLS models. The results obtained from the QUR test allow for more efficient and reliable interpretations of the data.

Furthermore, it becomes apparent that the asymmetric behavior varies across countries, highlighting the importance of considering country-specific factors in analyzing the dynamics of clean energy shares. The persistence changes for every other quantile.

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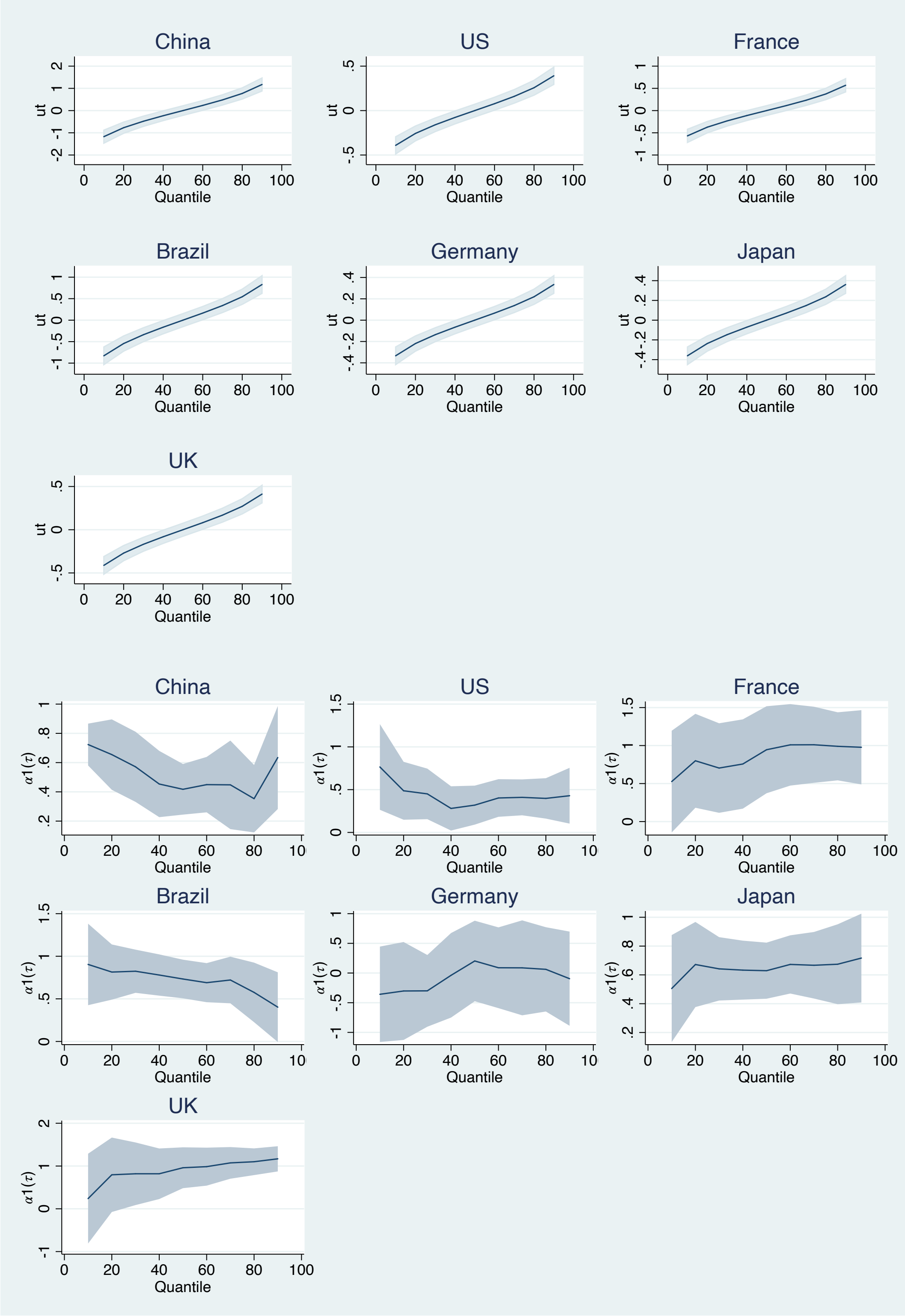
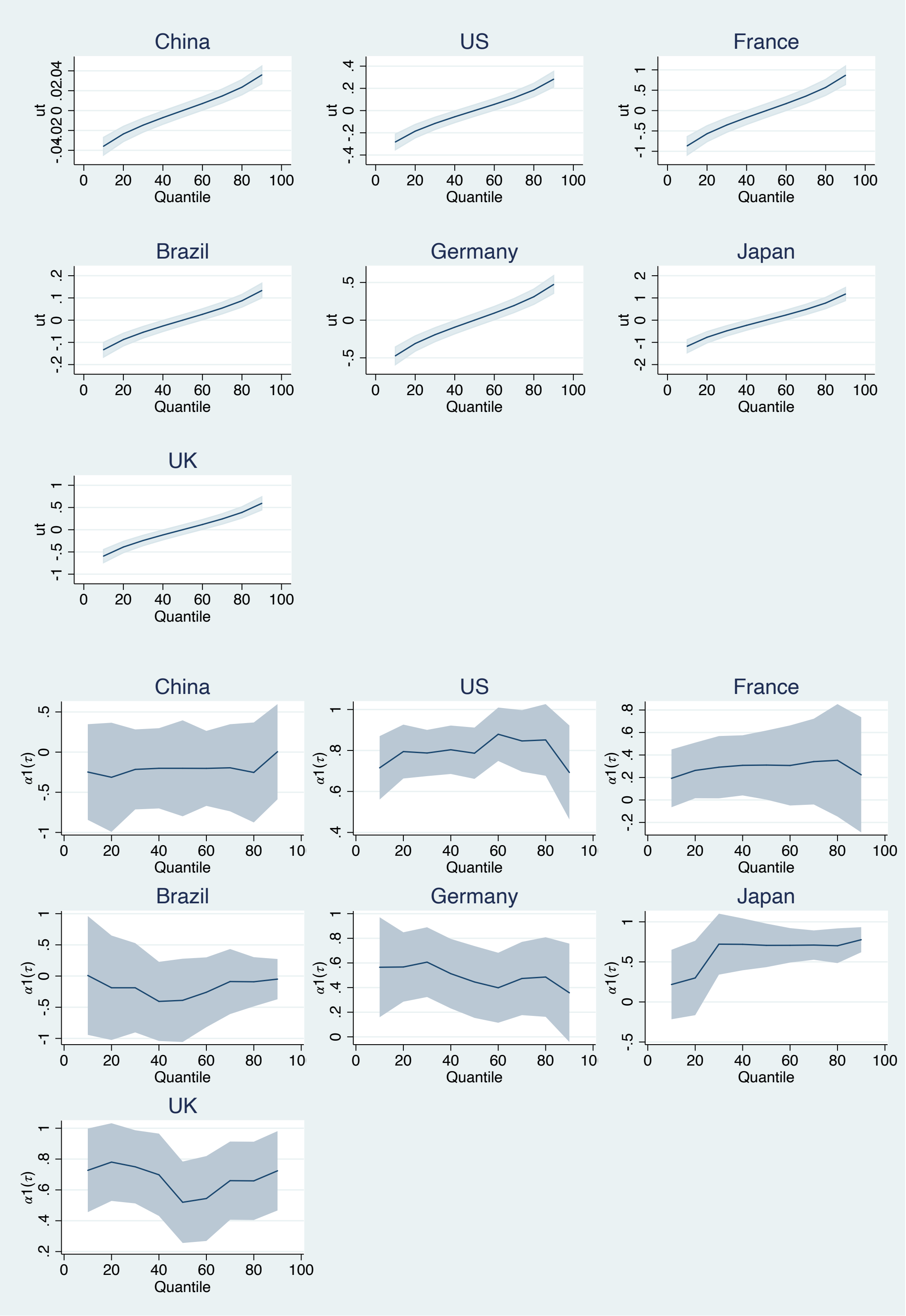
[8] A complete table of Hansen's critical values is given on Appendix A.



x-axis: quantiles & y-axis: coefficient values

$\alpha_1(\tau)$: sum of AR coefficients & u_t: magnitude of shock

Figure 3.4.3 Changes in the coefficients across quantiles by Countries: Share of Renewables



x-axis: quantiles & y-axis: coefficient values

$\alpha_1(\tau)$: sum of AR coefficients & u_t: magnitude of shock

Figure 3.4.4 Changes in the coefficients across quantiles by Countries: Share of Nuclear Energy

For instance, share of renewable series of China in the lower segment of Figure 3.4.3 shows higher persistence for the lowest and highest quantiles, which means that big negative and big positive shocks show longer memory than small shocks.

The analysis of the QUR test in Figures 3.4.3 and 3.4.4 reveals interesting country-specific patterns in the persistence behavior of the share of clean energy series. In the share of renewables series in Figure 3.4.3, China, the US, and Brazil exhibit high persistence for lower quantiles, indicating that high negative shocks have a long-lasting impact. In China, high persistence is also observed for higher quantiles, suggesting that both positive and negative shocks have a prolonged effect. France, Japan, and the UK show higher persistence for high quantiles, indicating that high positive shocks tend to be more persistent in these countries.

On the other hand, Figure 3.4.3 shows that in Germany, $\alpha_1(\tau)$ values range between -0.5 and 0. A negative persistence value is called anti-persistence.[9] In case of anti-persistence impact of the former value results in an increase for one period and a decrease for the other period. This periodic change causes an oscillation-like behavior in the time series (Di Vita, 2021). Since the oscillatory movement remains around a mean, persistence of the Germany series is regarded as mean reverting. Mean reverting behavior can be seen in the modified QUR estimation results of Germany, as well. For most of the quantiles the series is stationary.

Turning to the share of nuclear energy series in Figure 3.4.4, Brazil and China exhibit a similar pattern of anti-persistence, akin to what was observed in the renewable energy series for Germany. Japan, seems to display lower persistence for the lower quantiles, indicating a relatively shorter duration of the effects of shocks. This finding is controversial with QUR Test results. The United States and France show higher persistence for mild shocks, while the United Kingdom exhibits lower persistence for mild shocks. These country-specific patterns highlight the diverse dynamics and responses of the share of nuclear energy series to shocks across different countries.

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[9] Anti-persistence or anti-correlation is a phenomenon for the power grid and energy market analysis. (Lavicka and Kracik, 2017)

The QUR test provides valuable insights into the persistence behavior of the share of clean energy series, allowing for a more comprehensive understanding of the stochastic dynamics. By considering different quantiles, the analysis captures the asymmetric responses to shocks and sheds light on the varying degrees of persistence in different countries. These findings contribute to a more nuanced understanding of the behavior of clean energy shares and can inform policymakers and researchers in their efforts to promote sustainable and resilient energy systems.

Analyzing the Koenker and Xiao's QUR Test in Tables 3.4.6 and 3.4.7 and the modified QUR Test results in Tables 3.4.8 and 3.4.9, a noteworthy observation is the increased occurrence of stationarity cases upon introduction of sharp and smooth breaks. Most of the series show explosive behavior without breaks on Table 3.4.6 and 3.4.7. Even after the introduction of structural breaks, select series of France and the UK show unit roots, while in all other series largest autoregressive root $\alpha_1(\tau)$ is lower than unity.

QKS test results in stationarity only for three cases when structural breaks are considered, Germany's share of renewables and share of nuclear energy series, as well as France's share of nuclear energy series. This result is intuitive when we consider the German discipline reflected on the energy policies and France's resilience in development of its nuclear energy sector. Notably, the series depicting the share of renewables and the share of nuclear energy exhibit asymmetric dynamics. Typically, when mild shocks occur, those around the median, the shares series demonstrate a transitory behavior within the renewable and nuclear energy sectors. It is important to note that the persistence patterns differ among countries, as certain countries experience persistent high positive shocks, while others face persistent high negative shocks.

In the subsequent parts 4.3.1 and 4.3.2, we provide a comprehensive overview of the behavioral patterns within the clean energy sector for each country. Furthermore, the Discussion section delve into additional information regarding policy interventions involving negative or positive shocks.

Table 3.4.6 Quantile Unit Root Test Results: Share of Renewables without breaks

	Quantiles	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
China	αOLS: 1.129									
	$\alpha_1(\tau)$	1.135	1.122	1.120	1.113	1.127	1.140	1.164	1.140	1.123
	$t_n(\tau)$	6.441	5.617	4.462	3.695	3.872	4.481	5.727	4.567	2.187
	δ^2	0.056	0.114	0.064	0.124	0.166	0.108	0.147	0.147	0.188
	10% Hansen CV	-1.889	-2.012	-1.907	-2.032	-2.114	-1.999	-2.078	-2.076	-2.156
	10% Bootstrap CV	-1.350	-1.832	-1.906	-2.032	-1.888	-1.223	-1.295	-2.003	-2.319
	Half-Life	∞	∞	∞	∞	∞	∞	∞	∞	∞
	QKS: 1.362									
US	αOLS: 0.983									
	$\alpha_1(\tau)$	1.130	1.055	0.991	0.925	0.930	0.877	0.918	1.035	0.947
	$t_n(\tau)$	1.210	0.491	-0.112	-0.976	-0.844	-1.350	-0.830	0.390	-0.769
	δ^2	0.214	0.394	0.473	0.551	0.577	0.569	0.556	0.510	0.168
	10% Hansen CV	-2.205	-2.511	-2.625	-2.728	-2.760	-2.749	-2.734	-2.676	-2.118
	10% Bootstrap CV	-1.987	-2.105	-2.187	-2.255	-2.191	-2.124	-2.170	-2.326	-2.418
	Half-Life	∞	∞	77.495	8.910	9.595	5.266	8.131	∞	12.689
	QKS: -1.350									
France	αOLS: 1.183									
	$\alpha_1(\tau)$	1.182	1.129	1.174	1.153	1.115	1.132	1.108	1.248	1.240
	$t_n(\tau)$	0.844	3.279	3.816	3.024	2.882	1.591	1.654	2.975	4.652
	δ^2	0.176	0.266	0.333	0.431	0.457	0.428	0.384	0.393	0.505
	10% Hansen CV	-2.140	-2.319	-2.429	-2.573	-2.610	-2.569	-2.505	-2.520	-2.676
	10% Bootstrap CV	-2.101	-2.089	-2.223	-2.525	-2.530	-2.337	-2.195	-2.330	-2.333
	Half-Life	∞	∞	∞	∞	∞	∞	∞	∞	∞
	QKS: 0.844									
Brazil	αOLS: 0.814									
	$\alpha_1(\tau)$	0.965	0.982	0.967	0.968	0.970	0.989	0.970	0.976	1.001
	$t_n(\tau)$	-0.408	-0.208	-0.877	-0.771	-0.745	-0.224	-0.569	-0.335	0.008
	δ^2	0.246	0.343	0.407	0.490	0.489	0.503	0.484	0.440	0.352
	10% Hansen CV	-2.283	-2.444	-2.540	-2.657	-2.655	-2.673	-2.647	-2.585	-2.459
	10% Bootstrap CV	-1.554	-1.846	-2.072	-2.046	-2.098	-2.049	-2.249	-2.196	-2.128
	Half-Life	19.576	37.769	20.688	21.538	22.930	62.986	22.618	28.363	∞
	QKS: -0.877									
Germany	αOLS: 1.077									
	$\alpha_1(\tau)$	1.036	1.063	1.060	1.090	1.112	1.115	1.121	1.111	1.143
	$t_n(\tau)$	0.825	1.322	1.993	4.297	4.871	5.566	4.442	1.689	2.133
	δ^2	0.056	0.053	0.101	0.096	0.105	0.107	0.110	0.097	0.062
	10% Hansen CV	-1.889	-1.884	-1.983	-1.974	-1.992	-1.997	-2.003	-1.977	-1.901
	10% Bootstrap CV	-1.388	-1.801	-1.701	-1.582	-1.354	-1.455	-1.823	-1.995	-2.348
	Half-Life	∞	∞	∞	∞	∞	∞	∞	∞	∞
	QKS: 0.825									
Japan	αOLS: 1.088									
	$\alpha_1(\tau)$	0.902	0.906	0.946	1.037	1.061	1.130	1.114	1.159	1.217
	$t_n(\tau)$	0.256	0.532	1.220	1.702	1.511	1.469	2.147	2.659	4.875
	δ^2	0.171	0.314	0.335	0.370	0.399	0.396	0.360	0.348	0.369
	10% Hansen CV	-2.124	-2.381	-2.416	-2.472	-2.518	-2.513	-2.457	-2.439	-2.470
	10% Bootstrap CV	-2.295	-2.135	-2.070	-2.113	-1.923	-1.833	-1.821	-2.076	-2.015
	Half-Life	6.700	7.009	12.571	∞	∞	∞	∞	∞	∞
	QKS: 0.256									
UK	αOLS: 1.154									
	$\alpha_1(\tau)$	1.010	1.125	1.127	1.125	1.173	1.217	1.215	1.273	1.296
	$t_n(\tau)$	0.148	2.173	3.192	3.370	4.750	3.860	4.049	5.117	5.839
	δ^2	0.013	0.038	0.013	0.061	0.048	0.037	0.086	0.017	0.065
	10% Hansen CV	-1.796	-1.850	-1.795	-1.900	-1.872	-1.850	-1.954	-1.805	-1.908
	10% Bootstrap CV	-1.705	-1.491	-1.457	-1.317	-1.072	-0.970	-0.869	-1.574	-1.934
	Half-Life	∞	∞	∞	∞	∞	∞	∞	∞	∞
	QKS: 0.148									

Reject the Unit Root null hypothesis with: ***t-stat<0.01 bootstrap CV, ** t-stat <0.05 bootstrap CV, * t-stat <0.1 bootstrap CV
Grey shaded cells are stationary cases with Hansen (2005) critical values.

Table 3.4.7 Quantile Unit Root Test Results: Share of Nuclear Energy without breaks

	Quantiles	**0.1**	**0.2**	**0.3**	**0.4**	**0.5**	**0.6**	**0.7**	**0.8**	**0.9**
China	αOLS: 1.083									
	$\alpha1(\tau)$	0.984	1.020	1.020	1.072	1.095	1.117	1.139	1.143	1.171
	$tn(\tau)$	-0.449	0.605	0.673	1.905	2.858	4.354	5.429	4.085	2.207
	$\delta2$	0.201	0.032	0.062	0.195	0.127	0.022	0.049	0.034	0.154
	10% Hansen CV	-2.180	-1.837	-1.902	-2.169	-2.037	-1.816	-1.875	-1.842	-2.090
	10% Bootstrap CV	-0.917	0.000	-0.011	-0.002	0.000	-0.702	-1.557	-2.111	-2.716
	Half-Life	43.186	∞	∞	∞	∞	∞	∞	∞	∞
	QKS: -0.506									
US	αOLS: 0.974									
	$\alpha1(\tau)$	0.965	0.957	0.973	0.980	0.995	0.986	0.998	0.944	0.918
	$tn(\tau)$	-0.883	-2.395*	-1.440	-1.061	-0.159	-0.340	-0.032	-0.765	-0.824
	$\delta2$	0.151	0.266	0.353	0.427	0.510	0.598	0.651	0.565	0.561
	10% Hansen CV	-2.085	-2.300	-2.445	-2.559	-2.676	-2.784	-2.843	-2.745	-2.740
	10% Bootstrap CV	-2.479	-2.360	-2.219	-2.245	-2.513	-2.734	-2.683	-2.723	-3.058
	Half-Life	19.646	15.641	25.427	33.622	140.047	47.843	392.451	12.061	8.144
	QKS: -2.395									
France	αOLS: 0.935									
	$\alpha1(\tau)$	0.938	0.978	0.994	0.995	0.968	0.969	0.954	0.956	0.942
	$tn(\tau)$	-1.004	-0.521	-0.636	-0.843	-1.663	-0.921	-1.093	-1.114	-1.919
	$\delta2$	0.041	0.165	0.197	0.235	0.197	0.259	0.284	0.154	0.169
	10% Hansen CV	-1.858	-2.112	-2.173	-2.243	-2.173	-2.286	-2.331	-2.091	-2.121
	10% Bootstrap CV	-3.881	-3.055	-2.856	-2.762	-2.621	-2.591	-2.738	-2.871	-3.957
	Half-Life	29.730	71.508	64.429	45.289	21.676	37.038	23.467	16.482	7.532
	QKS: -1.919									
Brazil	αOLS: 0.814									
	$\alpha1(\tau)$	0.876	0.846	0.937	0.959	0.965	0.954	0.906	0.821	0.729
	$tn(\tau)$	-1.461	-3.177**	-1.566	-1.404*	-1.005**	-0.816*	-1.119	-1.586	-1.355
	$\delta2$	0.144	0.185	0.174	0.172	0.186	0.243	0.286	0.332	0.334
	10% Hansen CV	-2.071	-2.150	-2.130	-2.125	-2.153	-2.259	-2.335	-2.411	-2.414
	10% Bootstrap CV	-2.028	-1.773	-1.710	-1.115	0.000	-0.284	-1.388	-1.884	-2.349
	Half-Life	5.235	4.148	10.665	16.517	19.285	14.709	7.060	3.525	2.191
	QKS:-3.304									
Germany	αOLS: 1.024									
	$\alpha1(\tau)$	0.967	0.984	1.004	0.988	0.988	1.004	1.049	1.078	1.062
	$tn(\tau)$	-0.438	-0.428	0.159	-0.499	-0.477	0.155	1.647	2.975	0.830
	$\delta2$	0.149	0.302	0.315	0.319	0.394	0.437	0.471	0.468	0.376
	10% Hansen CV	-2.081	-2.362	-2.384	-2.390	-2.509	-2.575	-2.623	-2.619	-2.482
	10% Bootstrap CV	-2.381	-2.349	-2.360	-2.077	-1.863	-2.128	-2.414	-2.491	-2.742
	Half-Life	20.684	44.203	∞	56.043	55.763	∞	∞	∞	∞
	QKS: -0.499									
Japan	αOLS: 0.963									
	$\alpha1(\tau)$	0.819	0.934	0.951	0.974	0.986	1.000	1.008	1.025	1.063
	$tn(\tau)$	-2.055**	-1.017	-0.950	-0.510	-0.508	-0.012	0.266	0.745	1.006
	$\delta2$	0.143	0.318	0.292	0.266	0.244	0.232	0.211	0.195	0.104
	10% Hansen CV	-2.070	-2.389	-2.344	-2.300	-2.260	-2.239	-2.199	-2.170	-1.991
	10% Bootstrap CV	-1.637	-1.620	-1.214	-0.655	-1.367	-1.944	-1.923	-1.743	-1.594
	Half-Life	3.467	10.082	13.746	26.169	50.341	1897.868	∞	∞	∞
	QKS: -2.055									
UK	αOLS: 0.984									
	$\alpha1(\tau)$	0.981	0.948	0.974	1.020	1.011	1.023	1.016	0.978	0.913
	$tn(\tau)$	-0.403	-0.630	-0.392	0.327	0.172	0.338	0.207	-0.155	-0.843
	$\delta2$	0.114	0.303	0.406	0.461	0.478	0.526	0.557	0.575	0.502
	10% Hansen CV	-2.011	-2.363	-2.529	-2.608	-2.632	-2.696	-2.735	-2.757	-2.665
	10% Bootstrap CV	-2.913	-2.686	-2.748	-2.410	-2.360	-2.502	-2.519	-2.643	-2.667
	Half-Life	36.111	13.041	26.581	∞	∞	∞	∞	30.467	7.572
	QKS: -0.843									

Reject the Unit Root null hypothesis with: ***t-stat<0.01 bootstrap CV, ** t-stat <0.05 bootstrap CV, * t-stat <0.1 bootstrap CV

Grey shaded cells are stationary cases with Hansen (2005) critical values.

Table 3.4.8 Quantile Unit Root Test Results: Share of Renewables with sharp and smooth breaks

	Quantiles	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
China	αOLS: 0.494									
	$\alpha 1(\tau)$	0.723	0.655	0.571	0.454	0.417	0.449	0.448	0.353	0.635
	$tn(\tau)$	-3.864*	-2.867	-3.575**	-4.820***	-6.733***	-5.809***	-3.648*	-5.607***	-2.075
	$\delta 2$	0.013	0.025	0.030	0.051	0.065	0.068	0.059	0.019	0.101
	10% Hansen CV	-1.796	-1.823	-1.833	-1.878	-1.908	-1.914	-1.897	-1.808	-1.984
	10% Bootstrap CV	-3.827	-3.263	-3.252	-2.936	-2.447	-2.733	-3.247	-4.008	-6.801
	Half-Life	2.141	1.636	1.238	0.877	0.793	0.866	0.863	0.666	1.524
	QKS: -6.733									
US	αOLS: 0.421									
	$\alpha 1(\tau)$	0.765	0.487	0.450	0.281	0.319	0.403	0.410	0.398	0.429
	$tn(\tau)$	-0.905	-3.071	-3.747*	-5.418**	-5.657***	-5.988***	-6.052***	-5.338**	-3.208
	$\delta 2$	0.314	0.163	0.328	0.326	0.372	0.305	0.315	0.144	0.086
	10% Hansen CV	-2.382	-2.108	-2.405	-2.401	-2.476	-2.367	-2.383	-2.071	-1.952
	10% Bootstrap CV	-4.568	-3.685	-3.567	-3.643	-3.541	-3.493	-3.570	-3.770	-5.301
	Half-Life	2.589	0.963	0.869	0.545	0.607	0.762	0.777	0.752	0.819
	QKS: -6.052									
France	αOLS: 0.968									
	$\alpha 1(\tau)$	0.526	0.800	0.704	0.757	0.945	1.009	1.011	0.990	0.977
	$tn(\tau)$	-1.453	-0.695	-1.014	-0.870	-0.204	0.037	0.039	-0.040	-0.091
	$\delta 2$	0.044	0.195	0.277	0.307	0.289	0.314	0.405	0.279	0.119
	10% Hansen CV	-1.864	-2.169	-2.319	-2.371	-2.340	-2.382	-2.527	-2.322	-2.022
	10% Bootstrap CV	-3.889	-3.233	-3.191	-3.195	-3.052	-3.268	-3.229	-3.292	-3.946
	Half-Life	1.079	3.102	1.976	2.495	12.252	∞	∞	69.514	30.247
	QKS: -1.453									
Brazil	αOLS: 0.645									
	$\alpha 1(\tau)$	0.904	0.815	0.824	0.780	0.733	0.690	0.721	0.576	0.403
	$tn(\tau)$	-0.395	-1.105	-1.281	-1.933	-2.272	-2.679	-2.132	-2.391	-3.043
	$\delta 2$	0.111	0.214	0.226	0.240	0.280	0.229	0.209	0.196	0.325
	10% Hansen CV	-2.005	-2.205	-2.227	-2.254	-2.325	-2.232	-2.197	-2.172	-2.400
	10% Bootstrap CV	-7.158	-4.292	-4.354	-4.428	-4.584	-4.487	-4.548	-4.912	-7.585
	Half-Life	6.878	3.383	3.583	2.786	2.233	1.868	2.122	1.256	0.762
	QKS: -3.043									
Germany	αOLS: -0.161									
	$\alpha 1(\tau)$	-0.358	-0.302	-0.300	-0.039	0.203	0.089	0.087	0.062	-0.095
	$tn(\tau)$	-16.454***	-11.404***	-4.582***	-4.314***	-2.831**	-2.831*	-3.600*	-3.321	-3.198
	$\delta 2$	0.000	0.007	0.083	0.058	0.062	0.040	0.118	0.025	0.051
	10% Hansen CV	-1.767	-1.782	-1.946	-1.893	-1.902	-1.854	-2.019	-1.822	-1.878
	10% Bootstrap CV	-3.639	-3.075	-2.604	-2.115	-2.245	-2.790	-3.263	-4.239	-6.953
	Half-Life	-	-	-	-	0.435	0.286	0.284	0.249	-
	QKS: -16.454**									
Japan	αOLS: 0.644									
	$\alpha 1(\tau)$	0.505	0.672	0.642	0.633	0.629	0.673	0.667	0.674	0.717
	$tn(\tau)$	-2.784	-2.173	-3.051	-3.582	-3.964*	-3.160	-2.870	-2.322	-1.838
	$\delta 2$	0.050	0.241	0.160	0.201	0.244	0.199	0.202	0.103	0.245
	10% Hansen CV	-1.876	-2.255	-2.103	-2.181	-2.261	-2.176	-2.184	-1.988	-2.262
	10% Bootstrap CV	-5.161	-4.081	-3.795	-3.763	-3.560	-3.558	-3.607	-3.840	-5.661
	Half-Life	1.015	1.744	1.563	1.516	1.496	1.748	1.711	1.757	2.081
	QKS: -3.964									
UK	αOLS: 0.615									
	$\alpha 1(\tau)$	0.239	0.795	0.819	0.819	0.960	0.986	1.073	1.100	1.168
	$tn(\tau)$	-1.499	-0.474	-0.489	-0.636	-0.174	-0.071	0.422	0.609	0.955
	$\delta 2$	0.006	0.034	0.022	0.022	0.041	0.022	0.019	0.053	0.024
	10% Hansen CV	-1.781	-1.843	-1.815	-1.816	-1.857	-1.816	-1.809	-1.883	-1.821
	10% Bootstrap CV	-3.049	-2.311	-2.071	-1.502	-1.162	-1.080	-1.994	-2.807	-5.683
	Half-Life	0.484	3.024	3.471	3.465	16.774	47.644	∞	∞	∞
	QKS: -1.499									

Reject the Unit Root null hypothesis with: ***t-stat<0.01 bootstrap CV, ** t-stat <0.05 bootstrap CV, * t-stat <0.1 bootstrap CV

Grey shaded cells are stationary cases with Hansen (2005) critical values.

Table 3.4.9 Quantile Unit Root Test Results: Share of Nuclear Energy with sharp and smooth breaks

	Quantiles	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
China	αOLS: -0.151									
	$\alpha 1(\tau)$	-0.248	-0.313	-0.215	-0.202	-0.202	-0.203	-0.195	-0.253	0.005
	$tn(\tau)$	-3.821**	-4.500***	-4.238***	-4.364***	-4.708***	-4.414**	-4.070**	-4.593**	-3.042
	$\delta 2$	0.232	0.027	0.121	0.066	0.070	0.001	0.022	0.076	0.044
	10% Hansen CV	-2.238	-1.828	-2.024	-1.911	-1.918	-1.769	-1.817	-1.932	-1.864
	10% Bootstrap CV	-1.720	-0.752	-0.115	-0.221	-1.052	-1.986	-2.604	-3.373	-6.376
	Half-Life	-	-	-	-	-	-	-	-	0.130
	QKS: -4.708									
US	αOLS: 0.779									
	$\alpha 1(\tau)$	0.715	0.795	0.788	0.804	0.787	0.879	0.847	0.851	0.693
	$tn(\tau)$	-3.752	-3.076	-4.101*	-3.375	-3.339	-1.830	-2.195	-1.606	-2.604
	$\delta 2$	0.043	0.177	0.149	0.333	0.276	0.348	0.253	0.232	0.325
	10% Hansen CV	-1.863	-2.136	-2.082	-2.414	-2.317	-2.437	-2.277	-2.238	-2.400
	10% Bootstrap CV	-5.662	-3.878	-3.851	-3.799	-3.885	-3.947	-4.020	-4.321	-6.612
	Half-Life	2.069	3.017	2.904	3.169	2.889	5.384	4.162	4.312	1.888
	QKS: -4.101									
France	αOLS: 0.267									
	$\alpha 1(\tau)$	0.192	0.263	0.291	0.308	0.310	0.307	0.341	0.352	0.224
	$tn(\tau)$	-6.560**	-5.677**	-5.316**	-4.978**	-4.721**	-4.122*	-3.231	-3.029	-2.978
	$\delta 2$	0.004	0.014	0.067	0.010	0.016	0.037	0.043	0.099	0.145
	10% Hansen CV	-1.775	-1.797	-1.912	-1.789	-1.802	-1.849	-1.862	-1.979	-2.073
	10% Bootstrap CV	-3.951	-3.669	-3.548	-3.570	-3.470	-3.569	-3.634	-3.805	-4.724
	Half-Life	0.421	0.518	0.562	0.588	0.592	0.587	0.644	0.665	0.463
	QKS: -6.560*									
Brazil	αOLS: -0.131									
	$\alpha 1(\tau)$	0.009	-0.188	-0.188	-0.407	-0.390	-0.260	-0.088	-0.092	-0.050
	$tn(\tau)$	-2.073	-3.111	-3.419*	-4.453**	-4.207**	-4.776**	-4.500**	-4.875*	-4.937
	$\delta 2$	0.033	0.108	0.128	0.092	0.000	0.101	0.055	0.049	0.066
	10% Hansen CV	-1.840	-1.999	-2.039	-1.965	-1.767	-1.985	-1.888	-1.874	-1.911
	10% Bootstrap CV	-6.189	-3.629	-3.338	-3.154	-3.016	-3.079	-3.235	-3.904	-7.948
	Half-Life	0.148	-	-	-	-	-	-	-	-
	QKS: -4.937									
Germany	αOLS: 0.424									
	$\alpha 1(\tau)$	0.565	0.567	0.607	0.513	0.445	0.399	0.474	0.486	0.358
	$tn(\tau)$	-2.812	-5.584**	-3.660	-3.994*	-4.633*	-11.350***	-5.825**	-6.298**	-6.386*
	$\delta 2$	0.061	0.060	0.155	0.052	0.109	0.068	0.205	0.059	0.261
	10% Hansen CV	-1.900	-1.899	-2.093	-1.882	-2.000	-1.915	-2.189	-1.897	-2.290
	10% Bootstrap CV	-5.973	-4.093	-3.883	-3.977	-4.006	-3.961	-3.960	-4.296	-6.270
	Half-Life	1.214	1.222	1.386	1.038	0.857	0.754	0.928	0.960	0.674
	QKS: -11.350**									
Japan	αOLS: 0.519									
	$\alpha 1(\tau)$	0.217	0.299	0.721	0.719	0.706	0.707	0.710	0.701	0.777
	$tn(\tau)$	-0.416	-2.828	-1.431	-1.554	-2.374	-3.705**	-3.365*	-5.031**	-4.175*
	$\delta 2$	0.080	0.170	0.244	0.225	0.200	0.185	0.081	0.117	0.011
	10% Hansen CV	-1.941	-2.122	-2.261	-2.226	-2.180	-2.151	-1.943	-2.017	-1.792
	10% Bootstrap CV	-4.540	-2.867	-2.489	-2.499	-2.785	-2.927	-3.120	-3.082	-3.991
	Half-Life	0.454	0.575	2.121	2.101	1.991	1.996	2.022	1.955	2.744
	QKS: -5.031									
UK	αOLS: 0.634									
	$\alpha 1(\tau)$	0.727	0.780	0.750	0.698	0.520	0.544	0.660	0.659	0.724
	$tn(\tau)$	-2.806	-1.710	-2.127	-2.535	-3.931*	-4.076*	-4.096*	-4.685*	-3.239
	$\delta 2$	0.076	0.160	0.188	0.269	0.279	0.295	0.276	0.266	0.193
	10% Hansen CV	-1.932	-2.103	-2.156	-2.304	-2.323	-2.350	-2.316	-2.300	-2.166
	10% Bootstrap CV	-5.656	-4.233	-3.994	-3.988	-3.911	-3.843	-4.013	-4.218	-6.024
	Half-Life	2.173	2.795	2.406	1.928	1.059	1.139	1.668	1.660	2.145
	QKS: -4.685									

Reject the Unit Root null hypothesis with: ***t-stat<0.01 bootstrap CV, ** t-stat <0.05 bootstrap CV, * t-stat <0.1 bootstrap CV

Grey shaded cells are stationary cases with Hansen (2005) critical values.

3.4.4. QUR Test Results for Share of Renewables

Comparing the test results in Table 3.4.6 and 3.4.8 for the share of renewables, the introduction of breaks in the share of renewables series for France and the UK did not result in any significant changes in persistence behavior. Tested by the modified QUR, these series continue to have unit roots after introduction of sharp and smooth breaks. However, the half-life values decrease, especially for the lower quantiles. Both countries remain vulnerable to various shocks, making this information crucial for policymakers. It highlights the need for swift action in response to negative shocks within the sector, by implementing counter positive shocks. Additionally, if policymakers intend to increase the share of renewable energy consumption, a one time positive shock to renewable consumption behavior would be sufficient. It is important to note that these actions are likely to have the desired impact, given that the series are nonstationary and do not revert to their long-term mean when faced with any type of shock.

In China and the US, unit root cannot be rejected by the modified QUR test for the highest and lowest quantiles, as shown in Table 3.4.8. High positive and high negative shocks to renewable energy series show persistence. Mild shocks are transitory. The transitory behavior of mild positive shocks means China and the US are reluctant towards changing their energy mix. They need significant distortions to increase their renewable consumption shares. Transitory behavior of mild negative shocks means once the choice of energy resource is renewable energy, this preference does not change easily. Transitory behavior of mild positive shocks means the choice of energy resource does not change easily towards renewable energy either. Only high negative or high positive shocks have an impact.

For China 0.1 quantile is found stationary at 10% level. This can be interpreted as the series mean reverting towards the highest negative shocks. The reason for this transitory behavior may be that when there were high negative shocks that would decrease renewable energy consumption, the Chinese government took action against these shocks to return renewable energy consumption to its previous path. The government is known to implement pro-renewable energy policies elaborately. These findings imply that the United States and China should exercise greater caution in mitigating negative shocks if they aim to maintain or increase their levels of renewable energy consumption.

In Germany, it is noteworthy that only positive shocks exhibit persistence for the share of renewables series, specifically for the 7th, 8th, and 9th quantiles in Table 3.4.8. This observation aligns with Germany’s strong commitment to achieving energy transition and emphasizes the proactive measures taken by the German government to safeguard against negative shocks that could potentially decrease the share of renewable energy consumption.

Table 3.4.8 depicts that in Brazil and Japan, unit root cannot be rejected for share of renewables series at any quantile by bootstrap critical values, except for Japan’s median quantile. However, when we consider Hansen’s (1995) critical values we see stationarity for some quantiles. Result for Japan series is similar to that of China. In Brazil, positive shocks are transitory at all levels while negative shocks show persistence. Brazil government should focus more on its renewable energy policies accounting for the precautions against negative shocks. By being more proactive, Brazil can ensure the stability and growth of its renewable energy sector.

3.4.5. QUR Test Results for Share of Nuclear Energy

Observing the results for nuclear energy in Tables 3.4.7 and 3.4.9, the analysis reveals that the share of nuclear energy series exhibits stationary behavior for all countries upon incorporating both sharp and smooth breaks. However, it is worth noting that for certain quantiles of the United States, Japan, and the United Kingdom, the unit root null hypothesis cannot be rejected with the modified QUR Test, as indicated by the Hansen (1995) and bootstrap critical values. This suggests that for these specific quantiles, the series may possess some degree of non-stationarity or long-term persistence. This indicates the need for continued monitoring and analysis of the persistence dynamics in these countries’ nuclear energy sectors.

When we focus on test with bootstrap critical values segment of Table 3.4.9, high positive shocks are persistent for China while all positive shocks are persistent for

France. This interpretation is in line with these two countries' attitude toward nuclear energy. We know that France has been promoting nuclear energy consumption historically. The French government continuously introduced new promoting policies, increased feed-in tariff rates and incentives to nuclear energy producers and consumers. Even if China has entered the sector recently, they are constantly increasing their nuclear energy consumption. The results also show that these countries do not risk any regression in nuclear energy sector, but positive shocks are allowed.

In Germany and Brazil, on the other hand, high negative shocks are persistent as shown in Table 3.4.9. Again, when we look at these countries' story of nuclear energy sector we can see the coherence with QUR results. Brazil and Germany have been cautious towards nuclear energy. Brazil's consumption levels are very low ever since the sector has been active, while Germany has decided to opt out of nuclear energy until 2022. Thus, high negative shocks have been persistent for these two countries. In Brazil, high positive shocks are also persistent because even if the sector is growing rather slowly, unlike Germany, country has been investing in and did not forego its nuclear energy sector.

In the UK and Japan all negative shocks are persistent. These countries' nuclear energy sectors are in decline. In Japan, all positive shocks are transitory while in UK, high positive shocks are persistent. Thus, we might conclude that UK is still promoting nuclear energy with caution. However, Japan's nuclear energy sector is not picking up in response to positive shocks in any level. We know that Fukushima (2011) Disaster resulted in an immediate decline in nuclear energy consumption, nullifying the previous increases. Thus, we must state that positive shocks are transitory especially because of Fukushima. It seems that the disaster had a permanent impact on Japan's nuclear energy sector. We can interpret that they are successful in implementing their anti-nuclear policies.

QUR Test with bootstrap critical values did not result in stationarity for the US. However, the test with Hansen (1995) critical values indicates that, while all negative shocks are transitory, positive shocks are persistent for the US, except for the 9th quantile. We can relate to the US result as the country did not decrease its share of nuclear energy consumption at any point in time. Transitory behavior of high positive shocks, corresponding to 9th quantile, may be a result of the country's reluctance against changing its energy mix prominently. Share of nuclear energy increases but the speed of growth of the series has decreased.

The introduction of structural breaks offers insights into the distinct persistence behaviors of renewable and nuclear energy series, which vary across countries. For instance, the renewable energy series for France and the UK do not exhibit stationarity using the modified QUR test, while their nuclear energy series show stationarity across almost all quantiles. This indicates that France and the UK need to focus more on policies protecting their vulnerable renewable energy sector, while their nuclear energy sector remains resilient. In China, high positive shocks are persistent for both renewable and nuclear energy series, reflecting the country's significant emphasis on clean energy. In Germany, positive shocks to the renewable energy series are persistent, whereas the nuclear energy series only show persistence towards negative shocks, indicating Germany's strong focus on renewable energy and reluctance towards nuclear energy. These results highlight the need for separate country-specific analysis of the two clean energy components.

3.5. Conclusion

This study investigates the country-specific developments in the 1950-2020 period for the shares of clean energy consumption in total primary energy consumption for France, Brazil, Germany, Japan and the UK. These countries are leaders in clean energy consumption with slowing nuclear energy consumption levels. China and the US are added to the country group of the analysis to capture the impact of the developments in clean energy sector for the countries who occupy the top two positions. Clean energy components, renewables and nuclear energy, has been examined separately and comparatively, allowing for tailored interpretations and policy recommendations based on countries and energy sources.

Historical events in the clean energy sector create shocks to the statistical components of the shares of renewable and nuclear energy series. Persistence responses to these events are crucial for informed industrial and political decisions. The long-memory characteristics of clean energy components in each country are examined, considering both sharp and smooth structural breaks. Also, asymmetric impacts of these shocks are analyzed using Quantile Unit Root (QUR) Test procedures. We found that temporary shocks to clean energy series result in both permanent and transitory effects, in a country- and resource-specific manner. When structural breaks are introduced, we see transitory effects for more cases especially for the mild shocks.

Conventional unit root tests without breaks cannot reject the unit root null hypothesis in any country. While ZA Test with one structural break identifies stationarity only for the renewable energy share of the US, LS Test allowing for two structural breaks more clearly supports the claim that the inclusion of structural breaks can result in stationarity for variables that are otherwise non-stationary. LS Test finds stationarity, except for the share of renewables of Japan and for the share of nuclear energy of France, Germany, and the UK. EL Test does not find stationarity in any case. Additionally, the break dates found by these tests do not correspond to the timing of historical developments in these series. The results for BP Test for multiple unknown structural breaks found better estimates. By the inclusion of smooth break terms in the BP procedure we have achieved to model the series more accurately.

The QUR Test allows diving deeper in the dynamics of the persistence behavior investigating of the entire distribution of a series. Results show that when QUR is performed without structural breaks we cannot detect stationarity neither in the renewable shares nor in the nuclear energy shares series. In this study unknown sharp and smooth break parameters are determined for each quantile in a modified QUR Test, employing the breaks in the alternative hypothesis. Incorporating structural breaks in each quantile in the unit root test procedure without subsequent detrending allows for better detection of the impact of those breaks in the asymmetric persistence behavior of the series. The modified QUR Test detects the impact of structural breaks and finds stationarity in a country-specific structure, emphasizing the distinct behavior of countries towards nuclear and renewable energy.

According to the results of the modified test, renewable energy shares of France and UK did not show stationarity even after introducing breaks for any quantile. In China, the US, and Japan unit root cannot be rejected by the modified QUR test for the highest and lowest quantiles meaning high positive and high negative shocks to renewable energy series show persistence. For China, and Japan 0.1 quantile is also found stationary. The reason for this transitory behavior towards big negative shocks may be that the Chinese and Japanese governments took action against these shocks to return renewable energy consumption to its previous path. In Germany, only positive shocks exhibit persistence for the share of renewables series. In Brazil, positive shocks are transitory at all levels while negative shocks show persistence.

The nuclear energy shares series show stationarity for certain quantiles in each country with the modified test, while conventional QUR Test results in non-stationarity. High positive shocks are persistent for China while all positive shocks are persistent for France. For the US, positive shocks are persistent, except for the 9th quantile, while all negative shocks are transitory. The results show that these countries do not risk any regression in nuclear energy sector, but positive shocks are allowed. On the other hand, in Germany and Brazil, high negative shocks are persistent. In UK and Japan all negative shocks are persistent. These countries' nuclear energy sectors are in decline. In Japan, all positive shocks are transitory while in UK, high positive shocks are persistent. Transitory behavior of positive shocks and persistence behavior of negative shocks to nuclear energy series is especially because of Fukushima.

If positive shocks are transitory, the governments need to choose continuous positive shocks like long-term renewable portfolio standards and feed in tariffs to boost clean energy consumption. If positive shocks are persistent, one-time positive shocks, such as fixed bonuses for the required amount of clean energy production are sufficient. In case of persistent negative shocks, if governments and the industry want the shares of clean energy consumption to increase, they need to respond by positive shocks to compensate for the losses from those negative shocks. The response should be designed according to the long-memory behavior of the positive shocks. If the country wants a nuclear energy phase out, they also need to act considering to the long-memory characteristics of their nuclear energy shares series in response to negative shocks.

The decline in nuclear consumption is primarily attributed to nuclear accidents. Countries that consider nuclear energy unsafe have shifted their focus towards renewable energy, leading to an increase in the share of renewables. It is worth noting that this is one of the reasons why the Kyoto Protocol is considered a break date especially for renewable energy but not for nuclear energy. The future of energy consumption is likely to rely on a diverse mix of technologies, but clean energy sources, particularly renewables, are expected to constitute a significantly larger share. Intergovernmental policies and corporate decisions, such as taxation on oil and gas companies, divestment strategies, and initiatives like flight shaming, have played a pivotal role in accelerating technological innovation in the clean energy sector.

Our findings by the QKS Test, testing the unit roots of the entire distribution of the clean energy shares series, results in stationarity only for three cases when structural breaks are considered: Germany’s share of renewables and share of nuclear energy series, as well as France’s share of nuclear energy series. Among the analyzed developed countries, not all but only these two show resilience to all types of shocks to clean energy series. This resilience may be provided by the institutional development levels of these countries. Our findings underline the importance of conducting country-specific studies to fully understand these dynamics.

The persistence response of any energy variable to shocks is of significant importance due to its indirect effects as well. Shocks to clean energy variables can lead to substantial changes in conventional energy usage, overall economic output, employment rates, and environmental indicators. This intricate correlation between energy and non-energy variables implies that high persistence in one domain can translate to high persistence in the other. Numerous studies on cointegration have indicated that energy variables share a long-term relationship with non-energy variables. Meng et al. (2013) noted that recent experiences have shown a negative correlation between economic growth and energy consumption in developed countries, while the correlation tends to be positive in developing countries. This suggests that the economies of developed countries have become progressively resilient in response to energy shocks.

Future studies should focus more on country-specific and resource-specific analysis. In case of data availability, examining impacts of the 2008 economic crisis, COVID-19 and the Russia-Ukraine war on clean energy series will reveal useful information. Allowing for the persistence parameter to change, responding to the structural breaks, may also provide new insights. Additionally, there is a gap in the country specific studies exploring cointegration between each clean energy components and environmental degradation. Such studies help to see if the distinct shocks to these series will result in common impacts.

CHAPTER 4

TIME-VARYING COINTEGRATING RELATION BETWEEN CO_2 EMISSIONS AND CLEAN ENERGY CONSUMPTION

This study aims to determine if there is a long-run relationship between CO_2 emissions and clean energy consumption and to explore the characteristics of this relationship. To gain a comprehensive understanding of the global clean energy sector, a country-specific analysis was conducted for ten countries with the highest levels of clean energy consumption: China, the US, France, Brazil, Germany, Russia, Canada, India, Japan, and the UK. Clean energy consumption includes both renewable and nuclear energy. We analyzed these series separately and comparatively, as each series operates according to its own dynamics, country-specific dynamics, and as substitutes for each other. Additionally, we used the share series of clean energy consumption instead of levels because the share series represent both environmental considerations and energy efficiency concerns. The study covers the timeline from 1950 to 2020, which includes the most prominent events leading to structural breaks in the relationship between emissions and clean energy consumption. The existence of structural breaks complicates the conclusions and interpretations of conventional tests for cointegration. In this study, Bierens and Martins' (2010) Time-Varying Cointegration Test was used, approximating structural breaks as smooth regime changes. The results show that when structural breaks are considered, CO_2 emissions are cointegrated with the shares of both clean energy components. GDP growth is found to have a dominant explanatory power over emissions. We found evidence that only in China, after the 2000s, increases in the growth of the share of renewables result in a decrease in emissions growth. Additionally, France and Germany exhibit a slight negative relation between nuclear energy shares and CO_2 emissions.

Keywords: energy economics, cointegration, time-varying parameters

4.1. **Introduction**

The world is currently undergoing an energy transition process aiming to reach net-zero carbon goals. Global spending on clean energy is at an all-time high. However, many countries, especially emerging and developing economies, still require substantial increases in investment to meet their climate and clean energy goals. It is not yet clear if CO_2 emissions are decreasing with increased clean energy consumption. This study aims to investigate the long-run dynamics between CO_2 emissions and clean energy consumption, considering GDP growth as an explanatory factor.

This topic is crucial due to rising environmental concerns, most recently highlighted by the Kyoto Protocol (1997-2005) and the Paris Agreement (2015). Achieving net-zero carbon targets is only possible by reducing production and consumption and transitioning to environmentally less harmful technologies for energy production. However, countries face a tradeoff between decreasing growth and increasing emissions. Analyzing the cointegration between CO_2 emissions, clean energy consumption, and economic growth helps establish a foundation for making the best political and market decisions.

Through international climate treaties, the relationship between carbon emissions and energy consumption has been emphasized, considering energy intensity and the type of energy used. Promoting clean energy consumption, especially from renewable sources, has become a primary goal. Environmental issues and energy transition commitments have merged through the Kyoto Protocol and the Paris Agreement. With the long-term commitments of the Paris Agreement, a universal recognition around net-zero carbon targets has emerged.

Recently, at COP28 in January 2024, the summit outlined five objectives to keep the 1.5°C target within reach. First of these objectives was to support the tripling of renewable energy capacity by 2030. Second was the aim to double the rate of global energy intensity improvements by 2030. Third goal was to ensure the orderly decline of fossil fuel use. Forth was to recognize the need for scaled-up investment. The last objective was to highlight the critical role and opportunity for the fossil fuel industry to reduce methane emissions from their operations, aiming for a 75% reduction by 2030. These objectives relate to the efficient allocation and cleaning of energy resources, with the main implication being the increase in the share of clean energy, particularly renewables.

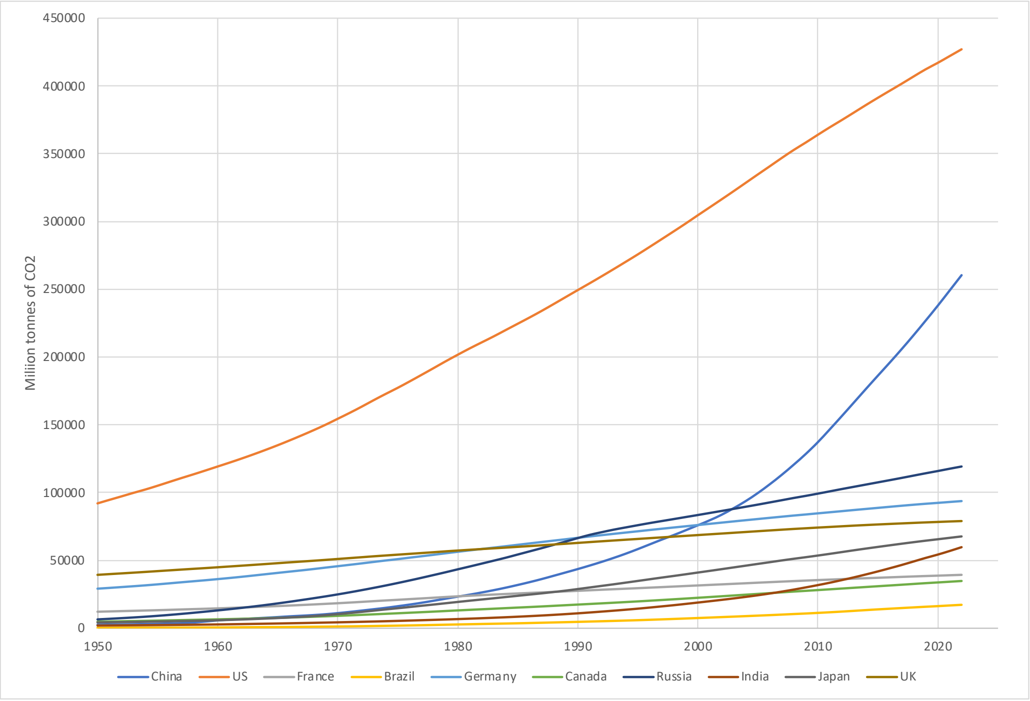

Figure 4.1.1 Cumulative CO2 emissions by major clean energy consumers.

Source: Global Carbon Budget (2023) – with major processing by Our World in Data

Despite global efforts, emissions continue to rise. The positive impact of these efforts on the environment appears limited to a slower increase in emissions rather than a decrease. Literature suggests that without international compliance, emissions for the EU would have increased by 12-50% by 2010, and for Japan, the increase would have been 20-33%. With the commitments of these "flawed" climate treaties, overall EU emissions have declined by 10%, and Japan’s emissions have increased by only 6% (Grubb, 2016).

Figure 4.1.1 shows the cumulative CO_2 emissions by the ten major clean energy consumers analyzed in this study: China, the US, France, Brazil, Germany, Canada, Russia, India, Japan, and the UK. There is a slight decrease in the growth rate of emissions for developed countries, while the slope is steeper for developing countries. Despite being the leading clean energy consumers, China and the US are also the world's leading emitters. The US, as a developed country, shows a slight slow-down in emissions growth compared to the fast increase in China, representing a developing country.

Considering the focus on clean energy as a strategy for climate change mitigation, the questions arise: “Do emissions and clean energy consumption have a long-term relationship? Has the world been able to couple emissions reductions with clean energy use?” To answer these questions, we need to determine if there is cointegration between emissions and clean energy consumption. This will enable us to predict developments in environmental degradation based on trends in clean energy consumption. In the third chapter we have found that renewable and nuclear energy show asymmetric responses towards negative and positive shocks and small and big shocks in a country- and resource specific manner. We could derive valuable policy implications tailored for each country. If there is cointegration between clean energy consumption and CO_2 emissions, we can infer that long-memory characteristics of clean energy components, will reflect upon the long-term behavior of emissions.

Demand-side effects on emissions are driven by economic growth and massive trade flows. High demand leads to increased energy consumption and industrial production, which has been extremely energy intensive. Our goal is to reduce emissions through cleaner energy consumption without lowering demand for growth. The impact of clean energy consumption on emissions represents a supply-side effect. Producing a high supply equivalent to high demand but with low emissions requires efficient and cleaner energy use. On the supply side, we firstly need increases in energy efficiency of production processes to lower total energy consumption per unit of industrial production, and secondly an increase in clean energy consumption in the production processes. We argue that analyzing the clean energy shares series addresses these two supply-side requirements. For emissions to decrease without hindering economic growth, we need higher shares of clean energy along with increased energy efficiency. It is important to recognize that increase in clean energy shares leading to lower CO_2 emissions does not necessarily imply that energy efficiency has improved. However, if empirical results indicate that increasing the share of clean energy does not decrease CO_2 emissions, this could point to issues with energy efficiency and the rising levels of fossil fuel consumption, highlighting the interconnectedness of these indicators through industrial production and economic growth trajectories.

Increasing renewable energy consumption alongside fossil fuels has become common practice for both developed and developing countries, aiming to boost energy consumption, from all resources, needed for economic growth. However, climate change mitigation requries energy transformation, which means not only increasing clean energy consumption but also decreasing highly polluting energy consumption (coal and oil) (Xie et al., 2023). Measures considering renewable or nuclear energy consumption levels alone cannot indicate the reducing impact of clean energy on emissions. Any environmental analysis measure must incorporate total energy consumption. Contrary to existing literature, we argue that using share of clean resources instead of levels of clean energy consumption is more significant.

All countries have undergone an energy transition process, especially in the 2000s. It is evident that changes during this transition process impact both the unit root properties of environmental and energy-related variables and the statistical relationship between pollution and clean energy. Since 2010, the levelized cost of energy (LCOE) for solar PV technologies has dropped by around 60%. New storage technologies have also been developed for more secure capacity holdings, making it easier to increase renewable capacities. Among the countries in our study, in the past 15 years, the share of renewables has exceeded 20% rising from around 2% for most of them. These changes highlight the evolving role of clean energy in mitigating climate change and reducing carbon emissions.

This raises the question of whether the cointegration relationship has changed due to certain events. For instance, the 1970s oil crisis led countries to focus on alternative energy sources, especially nuclear energy, to achieve energy self-sufficiency. The

Kyoto Protocol (1997-2005) spurred rapid development in the clean energy sector, particularly renewables. Studies on clean energy conducted before the Fukushima Nuclear disaster should be reconsidered, as the accident was a significant turning point in the clean energy sector. Security concerns surrounding nuclear energy pressured the rapid development of renewables, potentially leading to increased use of renewables and significant emissions reductions from renewables, but not from nuclear energy. Asymmetric adjustments in the relationship between emissions and clean energy may result from certain events or intrinsic dynamics between the variables. In this study, we first examine time-invariant cointegration. Then, time-varying cointegration is investigated considering structural changes.

Pollution cannot be considered without accounting for economic growth. Studies from the 1990s propose an inverted U-shaped relationship (quadratic relation) when plotting environmental degradation indicators against GDP per capita. This suggests that economic growth initially has undesirable effects due to the transition from agriculture to industry but eventually mitigates these effects as the economy grows. At higher development levels, structural changes towards information-intensive industries and the services sector, coupled with environmental regulations and better technology, lead to a leveling off and gradual decline in environmental degradation. This phenomenon is known as the Environmental Kuznets Curve (EKC), named after Kuznets's 1955 study on income inequality and economic development.

An important drawback of the EKC hypothesis is that environmental degradation is not solely a function of economic growth. Ignoring other factors in this relationship may prevent us from finding cointegration. Consider a three-variable system of I(1) variables. Testing cointegration between only two variables results in an error term that includes the omitted I(1) variable, exhibiting non-stationary dynamics and failing to reject the unit root null for the error terms (Maddala and Kim, 1998).

Moreover, several studies have challenged the EKC, finding a monotonically increasing relationship between environmental degradation and economic growth (Islam et al., 2013). There are numerous measures of environmental degradation, such as CO_2 emissions, SO_2 emissions, and concentrations of harmful materials in soil and water. The impact of economic growth on each measure varies. The quadratic relation applies to pollutants with local short-term costs (e.g., sulfur, particulates, and fecal coliforms), but not to pollutants involving long-term and more dispersed costs (e.g., CO_2), which are increasing functions of economic growth (Arrow, 1995). Notably, CO_2 emissions, the most critical element of climate change, exhibit a monotonically increasing relationship with economic growth, posing a challenge to achieving net-zero carbon targets (Dinda, 2004).

Additionally, cultural divergence among countries and differences in mitigation management are the sociological factors that have impacts on emission but are unrelated to economic development levels. Consider two countries with similar levels of economic development: the US and Germany. Their approach to mitigation is completely different. The United States is not participating in any international treaty and focusing more on economic growth, while Germany is taking swift action prioritizing emission reductions over its economy. Thus, it is more sensible to accept that EKC cannot be valid for all countries.

The socio-cultural divergence, combined with economic development levels, necessitates country-specific studies. Emerging and developing economies still require significant investment increases to achieve their energy and climate goals. The net-zero carbon target seems unattainable for underdeveloped countries, lagging in the energy transition process. In these countries increasing natural gas consumption instead of renewable energy significantly reduces CO_2 emissions. Targeting fossil fuel consumption may be the next step in energy transition for countries like South Africa and India, where many villages still use “chulha” stoves for heating and cooking (Yergin, 2020; Uğur et al., 2023). These facts highlight the wide gap between environmental behaviors and energy requirements among countries. Therefore, country-specific studies are preferable to panel data methodologies for analyzing cointegration relationships.

Recent studies prefer combining two strands of environmental literature on cointegration: environment ~ energy consumption and environment ~ growth, analyzing the environment ~ economic growth ~ energy consumption framework using multivariate methodologies. Some studies add variables such as urbanization, health, investment, FDI, and trade openness to conceptualize their hypotheses (Jalil and Mahmoud, 2009; Islam et al., 2013; Iorember et al., 2021).

Previous work includes studies using Time-Invariant Cointegration Tests and Time-Varying Cointegration (TVC) Tests. In the Time-Invariant Cointegration strand, past studies focused on the CO_2 emissions, total energy consumption, and GDP relationship (Jalil and Mahmud, 2009; Soytaş and Sarı, 2009; Lean and Smyth, 2010; Hamit-Haggar, 2012; Esso and Keho, 2016; Shahbaz et al., 2016; Rahman and Abul Kasheem, 2017; Aftab et al., 2021). These studies find mixed results regarding cointegration and Granger causality. Considering both economic growth and total energy consumption with emissions in a VECM framework raises doubts about the consistency of the estimations because of the close correlation between energy consumption and GDP. Long-run equation with the emissions chosen as the most endogenous variable will result in misspecifications because of this high correlation. Therefore, it may be more plausible to explain emissions with either energy consumption or GDP in separate equations.

Recent studies concentrate more on the CO_2 emissions ~ renewable energy consumption ~ GDP relationship (Nguyen and Kakinaka, 2019; Kırıkkaleli and Adebayo, 2021; Apergis et al., 2010; Mbarek et al., 2018; Azam et al., 2021a; Azam et al., 2021b). Some studies incorporate additional factors such as patent applications and the financial development index (Kırıkkaleli and Adebayo, 2021) and Gross Capital Formation (Mbarek et al., 2018). Studies focusing on renewable energy find controversial results. Nguyen and Kakinaka (2019), using a panel of 107 countries, find that renewable energy consumption is positively associated with carbon emissions. Conversely, Kırıkkaleli and Adebayo (2021) find that global renewable energy consumption exerts a negative impact on global CO_2 emissions.

Apergis et al. (2010), Mbarek et al. (2018), Azam et al., (2021a and 2021b) involve nuclear energy consumption in the emissions ~ renewables relationship, comparable to our study considering both renewables and nuclear energy in terms of their long-term relationships to emissions. All four studies build their VECM around the CI relation of per capita emissions, per capita GDP, renewable energy consumption and nuclear energy consumption, using each parameter in a unique long-run equation. The problem with this framework is that including both renewable and nuclear energy consumption in one equation could mask the impact of both variables on emissions due to the association between the two clean energy variables. Historical analysis shows that when countries focus on one, they abandon or reduce the consumption of the other. For example, in the 1970s, some countries used nuclear energy to hedge against energy shortages after the oil crisis. However, following nuclear accidents and environmental concerns with nuclear waste management, these countries slowed down nuclear energy production while improving the renewable energy sector. Using these two variables in a VECM framework can lead to unstable coefficient estimates. Unlike the literature, our study builds two separate equations, one for renewables and one for nuclear energy, to uncover and compare the particular impact of the consumption of each clean resource on emissions.

Among the studies using both renewables and nuclear energy, Apergis et al. (2010) find a negative association between nuclear energy consumption and emissions but a positive relationship between renewable energy consumption and emissions. Azam et al. (2021a) find that clean energy consumption contributes to mitigating CO_2 emissions, but the effect of nuclear energy consumption is not strong. Azam et al. (2021b) find that renewable and nuclear energy have a positive impact on emissions for some countries and a negative impact on others. Mbarek et al. (2018) find that there is a long-run relationship between GDP and renewable energy consumption. The results are controversial, and there is no consensus in this field, which underscores the need for studies with novel methodologies. Previous Studies with Time-Invariant Cointegration use Johansen’s Methodology, Pesaran and Shin’s ARDL Bounds Test (1999), Larsson et al.’s Panel ECM (2001), Johansen Fisher Panel Cointegration Test (1988, 1991), Pedroni Panel Cointegration Test (1999, 2004), and Bayer and Hanck Cointegration test (2013).

All countries have undergone an energy transition process, especially in the 2000s. These changes impact both the unit root properties of the variables of interest and the relationship between energy variables and pollution. Previous time-invariant cointegration studies have ignored the time-varying characteristics of the economic effect and carbon reduction effect of the energy transition. The unit root tests that are the first step of the cointegration analysis are inconsistent without considering structural changes. Accepting that there are structural changes means not proceeding with Time-Invariant Cointegration Tests, as the results become inconsistent or misleading. More robust estimation techniques are needed.

Studies using Time-Varying Cointegration (TVC) Tests in the environment ~ clean energy literature are categorized by the variables of interest. Studies analyzing the TVC for CO_2 emissions ~ renewable energy consumption ~ GDP include Apergis and Payne (2014), Cai et al. (2018), Kang et al. (2019), Iorember et al. (2021), Xie et al. (2023), Dumrul et al. (2023). Apergis and Payne (2014) incorporate real coal prices, and real oil prices finding that renewable energy is positively affected by emissions. Cai et al. (2018) analyze the long-run relationship between emissions, clean energy consumption, and GDP, integrating sharp structural breaks found by Bai and Perron (2003) methodology into the ARDL Bounds Test. Unlike existing literature, they use clean energy as an aggregate of nuclear and renewable energy. However, they do not find cointegration for Canada, France, Italy, the US, and the UK. Kang et al. (2019) include non-renewable consumption, finding a positive short-run but negative long-run relation between hydro energy consumption and emissions. Iorember et al. (2021) add human capital development and trade flows and Xie et al. (2023) add coal, oil and natural gas consumption, both finding that increased renewable energy use improves environmental quality. Dumrul et al. (2023) consider globalization finding a negative relationship between renewable energy production and CO_2 emissions. Recent studies analyzing the TVC for CO_2 emissions ~ nuclear energy consumption include Irfan et al. (2022) and Özgür et al. (2022). Irfan et al. (2022) find that nuclear energy worsens the environment for developed countries, while Özgür et al. (2022) find that nuclear energy contributes to decreasing emissions in India.

Kang et al. (2019) and Xie et al. (2023) use TVP-VAR model of Sims (1980), Primiceri (2005), and Nakajima (2011) incorporating random walk time variation in the VAR parameters for the emissions ~ renewable energy relation. TVP-VAR is applied only to the stationary variables, requiring first differences in the emissions and clean energy variables, which is not preferred in our study for interpretation purposes. We are interested in the existence of the long-run relation in the context of cointegration, different from the TVP-VAR concept. However, the methodology used to incorporate time-varying parameters in the TVP-VAR is technically valuable in terms of understanding time-varying parameters methodologies.

Returning to the cointegration literature, previous studies with TVC use methods including Sharp breaks in CI relation: Panel Cointegration with breaks (Westerlund, 2006), Multiple structural breaks cointegration test (Maki, 2012); and Smooth breaks in CI relation: Time-Varying Coefficients Cointegration Test (Park and Hahn, 1999), TVC Test (Bierens and Martins, 2010), Fourier ADL Cointegration (Banerjee et al., 2017).

When considering cointegrated relationships, one must distinguish between breaks in the relationships and breaks in the individual variables. In this study, we did not model the structural breaks in the level or trend of the VECM. In the literature, determining the break dates and introducing them in a multivariate framework is argued to be complicated. Break detection is a complex issue, even for a univariate process. In multivariate frameworks, deterministic parameters are affected by all the variables jointly. Impacts of a break occurring in one variable may occur at different dates for another variable (Maddala and Kim, 1998). In such cases, true detection of the breaks is almost impossible in the deterministic part (level and/or trend) of the equation. Therefore, in a multivariate framework, using break detection methods in the parameters of individual variables may be technically more relevant.

The focus on time-varying cointegration between emissions, clean energy, and economic growth is necessary but with careful consideration. In their study incorporating sharp structural breaks, Cai et al. (2018) examine the cointegration between emissions and clean energy consumption, defined as a composite of renewable and nuclear energy. The approach of aggregating clean energy, while accounting for structural breaks, raises concerns about the validity of their findings. Renewable and nuclear energy have historically experienced distinct phases and structural breaks at different times. Additionally, in some countries, these energy sources act as substitutes for each other; a structural break in one can cause an opposing break in the other, thus masking the true impact on the aggregate clean energy variable.

Therefore, for any cointegration study that considers the relationship between emissions and clean energy, a more accurate assessment necessitates analyzing renewable and nuclear energy as separate variables. This allows for a comparative evaluation of their respective effects on emissions. Some studies have examined renewable and nuclear energy separately and comparatively in the time-invariant cointegration strand of emissions literature. Unlike the existing literature, recognizing that each clean resource exhibits different time-dependent characteristics, we use time-varying cointegration methodologies to understand their individual impacts on emissions.

In time-varying parameters methods, time is used as a proxy for unobserved factors affecting the coefficients of the model's explanatory variables, eliminating the need for quadratic forms of variables (Mikayilov et al, 2018). Additional terms like dummies for sharp breaks or smooth break terms result in over-parametrization and loss of degrees of freedom. Among the studies with time-varying cointegration, the studies allowing for time variation in CI parameters include Maki (2012) Multiple structural breaks CI Test, Park and Hahn (1999) Time-Varying Coefficients Cointegration Test and Bierens and Martins (2010) TVC Test.

The methodology of Maki Test involves dividing the dataset into subsets exerting regime-specific relations, which may not be desirable for short datasets. Since the switch from one regime to another is never sudden, models involving gradual structural change receive more attention (Maddala and Kim, 1998). Also, allowing for smooth changes could capture part of the impact of sharp breaks as well (Enders and Lee, 2012). Park and Hahn Test and Bierens and Martins Test provide smooth time variation in the parameters of the CI relation, estimated using the entire dataset. Bierens and Martins TVC Test has more intuitive recognition as it builds upon Johansen's CI framework which is highly preferred for the multivariate analysis.

Bierens and Martins Test serves our purposes better, so it is chosen over Maki (2012) Test and Park and Hahn (1999) Test.

Our study is the first to employ Bierens and Martins TVC Test in the context of long-run relationship between emissions ~ clean energy ~ economic growth. Recent studies using the Bierens and Martins Test in the emissions or energy literature include: Apergis and Payne (2014a), Apergis (2016), Destek et al. (2020), Uğur et al. (2023), Bahramian et al. (2023), Yılancı et al. (2023). Uğur et al. (2023) examine the long-term relationship between CO_2 emissions, oil, natural gas and coal consumption, and real GDP growth for India. They build the VECM with these five variables and they find that the parameters for GDP and coal consumption are the highest. The income and oil consumption elasticities of CO_2 emissions are increasing. They do not comment on the segments where parameters are negative and did not report the parameter for CO_2 emissions, modeled as a time-varying parameter in Bierens and Martins' methodology, while it is crucial since assessing the time-varying relation is only possible by observing the change in all parameters. Bahramian et al. (2023) examine the long-run relationship between aggregate clean energy consumption and economic growth in China, finding that clean energy promotes economic growth since 2005. During the oil crisis, economic growth resulted in more clean energy consumption, with a feedback relation between clean energy and economic growth in the interim. Time-varying parameters are not reported in their study.

In Apergis and Payne's (2014a) study, the cointegration between oil reserves and GDP is analyzed with a modification to Bierens and Martins' Test for panel cointegration. The analysis shows that coefficient for oil reserves is negative until 2003 and positive since then, indicating a monotonically increasing nature. The coefficient is negative for all times in resource-rich, labor-abundant countries. The study assumes that GDP and oil reserves have a monotonic relationship, restricting the order of Chebyshev's polynomials (m) to 1, showing limited variation. However, the coefficient may actually fluctuate, leading to different conclusions.

Apergis (2016), Destek et al (2020) and Yılancı et al (2023) study EKC using Bierens and Martins TVC Test. Apergis (2016) investigates EKC using squared GDP as an additional variable to emissions and level GDP values, rejecting the null hypothesis that the long-run coefficients are stable over time. He uses the quantile cointegration methodology of Xiao (2009), finding mixed results for individual countries at different quantiles. Yılancı et al. (2023) also use the quadratic form of GDP and energy consumption as factors in the long-run relation. They do not report the TVC parameters. The problem with Apergis (2016) and Yılancı et al. (2023) methodology is using unnecessary variables in the TVC framework. Since they incorporate the time variation in the GDP parameter, they should not use the quadratic form of the variable. Yılancı et al.'s estimations may be inconsistent because of the close relationship between energy consumption and GDP, with the additional squared GDP variable.

Destek et al. (2020) find that the emissions-reducing effect of economic growth is rational from 1973 to the 2000s, with emissions-increasing effect reappearing after 2007. They use Bierens and Martins' method to test for time variation in the cointegration relation, not reporting the TVC parameters, but using Balcılar et al. (2010) method for parameter estimations, reporting rolling coefficients of the VAR parameters. Balcılar et al (2010) use the bootstrap version of Toda and Yamamato (1995) VAR framework for testing granger causality in rolling window estimations.

A common preference in the long-run relation of emissions ~ clean energy ~ economic growth literature is using panel data (Apergis et al., 2010; Nguyen and Kakinaka, 2019; Azam et al., 2021b; Apergis and Payne, 2014b). According to Apergis (2016) the evidence from panel cointegration methodologies is mixed, possibly due to time dependence of cointegrating coefficients. Studies examining the emissions ~ clean energy relationship across multiple countries should use country-specific methodologies instead of panel analysis. EKC literature often prefers panel studies to incorporate data from many countries of varying development levels to see the inverted-U shape relationship between emissions and economic growth. Such studies do not guarantee that individual countries will move along the estimated relationship over time. Country-specific differences in mitigation capacities, social preferences and discount rates lead to different costs-benefits structures, implying different optimal pollution levels among countries, limiting the policy relevance of a collective EKC path estimate (Dinda, 2004).

There are a multitude of single country studies (Azam et al, 2021a; Kang et al, 2021; Fareed et al, 2023; Özgür et al, 2022; Xie et al, 2023; Dumrul et al, 2023). These studies provide valuable information on how the emissions and clean energy relations occur in individual countries, aiding in developing solutions for those countries or similar ones. We argue that emissions studies should analyze multiple countries separately and comparatively, showing how different characteristics result in different emissions ~ clean energy relationships. Single country studies do not address system-wide consequences of emission reductions. For example, CO_2 emissions reductions in one country may involve transfers of emissions to other countries, usually from developed to developing countries.

In countries where emissions have declined with rising income and increased clean energy shares, the reductions often result from local institutional reforms, such as environmental legislation and market-based incentives, ignoring international and intergenerational consequences. Thus, it is challenging to see the aftermath of emission reductions with either panel or single country analysis. There is a gap in the literature for studies that use country-specific characteristics of the relation between emissions and clean energy to develop a system-wide assessment. We focus on the ten countries with the highest clean energy consumption levels: China, the US, France, Brazil, Germany, Russia, Canada, India, Japan, and the UK. These countries are chosen as the analysis group because they shape the sector, while other countries with lower clean energy consumption levels either have little variation or have started clean energy consumption very recently. Analyzing these countries separately and comparatively provides a comprehensive picture for the development of emissions ~ clean energy relationship.

Many single-country studies in the literature cover relatively short time spans of 40-50 years. Testing cointegration in a multivariate framework, with high lag lengths for short time spans leads to over-parametrization, loss of degrees of freedom, and biased estimates. A common approach to address the short time span has been employing panel studies. However, for most of the macroeconomic variables, and especially for clean energy measures, true interpretation is not possible with panel data due to institutional, developmental and climatic differences, necessitating country-specific studies.

Country-specific analysis with a longer time series is preferred when data is available. The specific problem for clean energy data is that both renewable and nuclear energy do not have long histories. The study timelines cannot go earlier than the 1950s and need to start before the 1960s to see the impacts of the 1970s oil crisis and maybe the Suez crisis in 1957 on the clean energy sector. The earliest datasets in the cointegration literature between emissions and clean energy started in 1965 (Kang et al, 2019; Fareed et al, 2021). Our study contributes by investigating the cointegration relationship between the environment and clean energy with a more comprehensive data set from 1950 to 2020, covering significant events in clean energy history: the oil crisis, international environmental treaties (Kyoto Protocol in 1997-2005 and Paris Agreement in 2015), and the Fukushima Nuclear Disaster in 2011. This allows for incorporating the impacts of major events on the variables' relationships and modeling cointegration parameter behaviors more accurately.

Cointegration characteristics are affected by individual countries' heterogeneous characteristics, model specification, and econometric approach. Table 4.1.1 summarizes the literature discussed in this section. Mixed findings indicate a need for further investigation with advanced techniques, model specification, and country-specific analysis covering structural breaks affecting variable relationships. This study aims to contribute an analysis with these traits, utilizing Time-Varying Cointegration on the emissions ~ clean energy ~ economic growth relationship, using renewable energy and nuclear energy separately and comparatively, and using shares series as better clean energy measures. Analyzing the relation in the ten individual countries with the highest clean energy consumption levels over a time span that includes the impacts of the 1970s oil crisis, Kyoto Protocol, and 2011 Fukushima Disaster provides a significantly nuanced analysis in the cointegration between the environment and clean energy field.

The remainder of the study is organized as follows: Section 4.2 reviews our dataset and presents historical trends in CO_2 emissions, GDP, nuclear energy, and renewable energy from 1950 to 2020 at the country-specific level. Section 4.3 introduces the Time-Varying Cointegration methodology and compares it with previous methodologies in the literature. Section 4.4 presents the empirical results. Finally, the concluding section summarizes our findings and provides a discussion.

Table 4.1.1 Literature on cointegration between CO2 emissions and energy

Article	**Year**	**Timeline**	**Variable**	**Method**	**Results**
TIME INVARIANT COINTEGRATION					
Emissions-Energy Consumption-Economic Growth					
Jamil and Mahmud	2009	China: 1975-2005	CO_2 emissions energy consumption GDP growth foreign trade	**ARDL Bounds Test** (Pesaran and Shin (1999) and Pesaran et al. (2001) **Granger Causality wt VECM:** Estimate the required lag length for the short run dynamics β by AIC. In presence of CI estimate the ECM: $x_t = \alpha_1 + \sum_{i=1}^{p_1} \beta_{1,i} x_{t-i} + \sum_{i=1}^{p_2} \beta_{2,i} y_{t-i} + \sum_{i=1}^{p_3} \beta_{3,i} z_{t-i} + e_t$ $ECM_{t-1} = x_t - \hat{\alpha}_1 - \sum_{i=1}^{p_1} \hat{\beta}_{1,i} x_{t-i} - \sum_{i=1}^{p_2} \hat{\beta}_{2,i} y_{t-i} - \sum_{i=1}^{p_3} \hat{\beta}_{2,i} z_{t-i}$ $\Delta x_t = \alpha_1 + \sum_{i=1}^{p} \beta_{1,i} \Delta x_{t-i} + \sum_{i=1}^{p} \beta_{2,i} \Delta y_{t-i} + \sum_{i=1}^{p} \beta_{3,i} \Delta z_{t-i} + \lambda_1 x_{t-1} + \lambda_2 y_{t-1} + \lambda_3 z_{t-1} + \alpha_2 ECM_{t-1} + e_t$	Long-run relation exists. Causality: from GDP growth and energy consumption to CO_2 emissions
Soytaş and Sarı	2009	Turkey: 1960-2000	CO_2 emissions energy consumption GDP growth	Toda and Yamamato (1995) Granger Causality Method They then check for impulse responses.	No long-run relation between emissions and GDP
Lean and Smyth	2010	ASEAN: 1980–2006	CO_2 emissions energy consumption GDP growth	Johansen Fisher Panel Cointegration Test Panel version Pedroni (2001) Dynamic OLS	Unidirectional Gr causality from electricity consumption and emissions to economic growth.
Hamit-Haggar	2012	21 Canadian industrial sectors: 1990-2007	GHG emissions energy consumption GDP	Pedroni Panel Cointegration Test (1999,2004) Pedroni Fully Modified OLS (2000) for long-run relations Panel ECM (Pesaran et al., 1999)	EC and GHG emissions have a positive long-run relation. Economic growth and GHG emissions have a non-linear relation.
Islam et al.	2013	Bangladesh: 1970-2010	CO_2 emissions pc energy consumption pc GDP pc trade openness urbanisation	ARDL Bounds Test Granger Causality with VECM	EC and urbanization increases, trade openness decreases CO_2 emissions.

Table 4.1.1 (continued)

Esso and Keho	2016	African countries: 1971-2010	GDP growth energy consumption CO_2 emissions	ARDL Bounds Test Granger Causality with VECM	Cointegration exists
Shahbaz et al	2016	Next 11 countries: Bangladesh, Egypt, Indonesia, Iran, Mexico, Nigeria, Pakistan, Philippines, Turkey, South Korea, and Vietnam: 1972–2013	CO_2 emissions pc energy consumption pc real GDPpc,	ARDL bounds test. Time-varying Granger causality test: Sato et al. (2007)	Cointegration exists
Rahman and Abul Kasheem	2017	Bangladesh: 1972-2011	Industrial production growth energy consumption growth CO_2 Emissions growth	ARDL Bounds Test Toda and Yamamato (1995) Granger Causality Test	Cointegration exists One directional Causality: from industrial production and Energy consumption to Emissions.
Aftab et al.	2021	Pakistan: 1971-2019	CO_2 emission energy consumption economic progress	Johansen's Methodology ARDL Bounds Test Granger Causality with VECM	LR: EC, GDP growth have positive impact on CO_2 emissions.
Çıtak et al.	2021	Turkey: 1971-2017	CO_2 emissions Sectoral disaggregation of electricity consumption	Xiao's (2009) Quantile Cointegration Test	Positive effect of electricity cons. on CO_2 emissions wt higher impact on lowest and highest quantiles.
Emissions-Clean Energy Consumption-Economic Growth					
Apergis et al.	2010	19 developed countries: 1984–2007	CO_2 emissions Nuclear energy consumption Renewable energy consumption Economic growth	Panel ECM (Larsson et al, 2001) Panel Granger causality test	Negative association between nuclear energy and emissions. Positive relationship between renewable energy and emissions.
Mbarek et al.	2018	18 developed and developing countries: 1990-2013	CO_2 emissions pc GDP pc Gross Fixed Capital Formation Total labor force Renewable EC Nuclear EC	Pedroni Panel Cointegration Test (1999,2004) Kao Residual Panel Cointegration Test (1999) Engel and Granger Panel Granger causality test (1987)	Cointegration exists. LR relation between GDP and Renewable EC. Unidirectional causality from GDP to emissions and Nuclear EC for the developed countries.
Nguyen and Kakinaka	2019	107 countries: 1990-2013	Renewable energy consumption Non-renewable energy consumption Real GDP CO_2 emissions real oil price	Pedroni Panel Cointegration Test (1999,2004) Sadorsky (2009) Fully Modified OLS and DOLS estimations for LR relations	Low-income countries: REC is positively coreelated with carbon emissions. High-income countries: REC is negatively associaed with carbon emissions.

Table 4.1.1 (continued)

Azam et al.	2021	China: 1995-2017	CO_2 emissions Renewable EC Nuclear EC Fossil Fuels EC GDP Financial Development	Johansen's Methodology Fully Modified OLS Granger Causality with VECM	4 CI vectors Bi-directional causality: between Renewable EC and CO_2 emissions, Nuclear EC and CO_2 emissions, GDP and CO_2 emissions
Azam et al.	2021	US, Canada, India, Iran, Japan, Russia, UK, South Korea, Germany and China: 1990-2014	Natural gas Nuclear energy Renewable energy GDP CO_2 emissions	Pedroni Panel Cointegration Test (1999,2004)	RE and NE are vital to avoid global warming as well as to promote economic growth.
Kırıkkaleli and Adebayo	2021	World: 1985-2017	CO_2 emissions GDP Patent applications Financial Development Index Share of renewable consumption	Cointegration test: Bayer and Hanck (2013) Canonical cointegrating regression (CCR) methods: Stock and Watson (1993) Frequency-domain causality test: Breitung and Candelon (2006)	Increase in GDP is detrimental for the quality of the environment. REC exerts a negative impact on CO_2 emissions.
TIME-VARYING COINTEGRATION					
Emissions-Clean Energy Consumption-Economic Growth					
Apergis and Payne	2014b	Belize, Costa Rica, El Salvador, Guatemala, Honduras, Nicaragua, and Panama: 1980-2010	Renewable EC pc CO_2 emissions pc real GDP pc Real coal prices Real oil prices	Renewable energy is dependent variable. Panel Cointegration wt str breaks: Westerlund (2006) Uses Bai and Perron (2003) method to determine the structural breaks on the residuals of the long-run regression. Bootstrap to solve the cross-section dependence $RE_{it} = f(Y_{it}, CO2_{it}, RCOALP_{it}, ROILP_{it})$ Non- linear panel smooth transition VECM: Gonzalez et al. (2005) and Omay and Kan (2010) Panel version of Smooth Transition VECM $\Delta x_t = \alpha_1 + \alpha_2 ECM_{t-1} + \sum_{i=1}^{p} \alpha_{3,i} \Delta x_{t-i} + \sum_{i=1}^{p} \alpha_{4,i} \Delta y_{t-i} + \sum_{i=1}^{p} \alpha_{5,i} \Delta z_{t-i} + G(s_{t,}\gamma, c)\left[\beta_2 ECM_{t-1} + \sum_{i=1}^{p} \beta_{3,i} \Delta x_{t-i} + \sum_{i=1}^{p} \beta_{4,i} \Delta y_{t-i} + \sum_{i=1}^{p} \beta_{5,i} \Delta z_{t-i}\right] + e_t$ Where; $G(s_t, \gamma, c) = \left[1 + \exp\left(-\gamma \prod_{j=1}^{m} (s_t - c_j)\right]^{-1}$ And s_t is the transition variable, $H_0 \colon \gamma = 0$.	Assumes only one regime change (2002). Long run cointegration exists around a broken intercept. real GDP per capita, carbon emissions per capita, real oil prices, and real coal prices each has a positive and statistically significant impact on renewable energy consumption per capita.
Cai et al.	2018	Canada, France, Japan, Germany Italy, the US and the UK: ~1965 to 2015	CO_2 emissions pc GDP pc Clean EC	ARDL Bounds Test: McNown et al. (2018) Includes the structural break dummies in VECM determined by Bai and Perron (2003)	CI between real GDP per capita, clean energy consumption and CO_2 emissions only in Germany and Japan.

Table 4.1.1 (continued)

Kang et al	2019	India: 1965:1-2015:4)	CO_2 emissions Renewable (hydro) EC Non-renewable (coal) EC Economic growth	TVP-VAR: Nakajima (2011)	Impulse response of GDP from a positive shock to CO_2 varies with the type of energy use in different time horizons.
Iorember et al	2021	South Africa: 1990-2016	Ecological footprint pc Real GDP pc Renewable EC pc Human capital development Trade flows	Multiple structural breaks cointegration tests: Maki (2012) Dynamic unrestricted ECM through ARDL VECM Granger causality tests	Increase in renewable energy use, human capital, and trade improves environmental quality.
Irfan et al	2022	France, Germany, US, Canada, Japan, UK: 1980-2020	CO_2 emissions Nuclear EC	Time-Varying Bootstrap Granger Causality: Balcılar et al (2010)	Consumption of nuclear energy worsens the environment
Özgür et al	2022	India: 1970-2016	CO_2 emissions GDP pc Nuclear EC pc	Fourier ARDL cointegration: Banerjee et al. (2017)	NEC reduces air pollution
Xie et al.	2023	China: 1980-2019	CO_2 emissions Coal, oil, natural gas and renewable energy consumption Real GDP	TVP-VAR: Sims (1980), Primiceri (2005) and Nakajima (2011) $y_t = c_t + B_{1,t}y_{t-1} + B_{2,t}y_{t-2} + B_{p,t}y_{t-p} + e_t$ $B_{1,t}$, $B_{2,t}$, $B_{p,t}$ are time variant $B_t = B_{t-1} + v_{Bt}$ is random walk Time-varying Granger Causality: Rossi and Wang (2019) $H_0\colon \theta_t = 0\ where\ \theta_t\ is\ the\ related\ subset\ of\ B_t$	Expansion of REC restrained CO_2 emissions. But after 1990, this inhibitory effect weakened.
Dumrul et al	2023	Turkey: 1971-2006	CO_2 emissions Renewable energy production Economic growth Economic globalization	Fourier ARDL cointegration: Banerjee et al. (2017)	Negative relationship between renewable energy production and CO_2 emissions
Emissions or Energy Literature using Bierens and Martins TVC Test					
Apergis and Payne	2014a	Algeria, Bahrain, Kuwait, Libya, Oman, Qatar, Saudi Arabia, Syria, UAE, and Yemen: 1990–2013	Real GDP per capita crude oil reserves Controlling for: avg yrs of schooling real trade openness private inv. exp. FDI property rights international trade etc.	**Time-varying Cointegration:** Bierens and Martins (2010) for panel with m=1	TVC Exists Coefficient for oil reserves is negative up to 2003. Then positive.

Table 4.1.1 (continued)

Apergis	2016	Austria, Belgium, Canada, Denmark, Finland, France, Italy, Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, UK, US: 1960–2013	CO_2 emissions per capita GDP per capita	**Time-varying Cointegration:** Bierens and Martins (2010) Xiao's (2009) Quantile Cointegration Test	TVC exists. Mixed cointegration results for individual countries at different quantiles.
Mikayilov et al	2018	Austria, Belgium, Denmark, Finland, France, Germany, Italy, Netherlands, Norway, Sweden, Switzerland, and the UK: 1861- 2015	CO_2 emissions per capita GDP per capita	**Time-varying Cointegration:** Park and Hahn (1999)	TVC exists. Income elasticity of CO_2 emissions is positive.
Destek et al	2020	Canada and Japan, France, Germany, Italy, UK, US: 1800's-2010	CO_2 emissions per capita GDP per capita	**Time-varying Cointegration:** Bierens and Martins (2010) Bootstrap rolling window estimation: Balcilar et al. (2010)	TVC exists. Emissions-increasing effect of economic growth reappears in almost all countries, especially after 2007.
Uğur et al	2023	India: 1980: Q1- 2021: Q3	Growth rate of real GDP Oil, natural gas and coal consumption CO_2 emissions	**Time-varying Cointegration:** Bierens and Martins (2010) TVP-VAR: Primiceri (2005)	TVC exists. Increase in income and fossil fuel consumption have a positive impact on environmental degradation.
Bahramian et al	2023	China: 1980 - 2020	Clean energy consumption per capita GDP per capita	**Time-varying Cointegration:** Bierens and Martins (2010) Recursive and Rolling Granger Causality: Shi et al (2018)	TVC exists. Clean energy promotes economic growth since 2005.
Yılancı et al	2023	UK: 1850 - 2018	CO_2 emissions per capita GDP per capita Energy consumption per capita	**Time-varying Cointegration:** Bierens and Martins (2010) Recursive and Rolling Granger Causality: Shi et al (2018)	TVC exists. Energy consumption pollutes the environment significantly. The magnitude of its impact is affected by many shocks.

4.2. Data

For this analysis, we focus on the following countries with the highest levels of clean energy consumption: China, the US, France, Brazil, Germany, Canada, Russia, India, Japan, and the UK. The study covers the period from 1950 to 2020. GDP per capita series are sourced from the Maddison Project and are measured in international USD with 2017 prices. CO_2 emissions data is obtained from the Global Carbon Budget (2023) and measured in tonnes. This pollution indicator records as cumulative CO_2 emissions from fossil fuels and industry, excluding land use change, deforestation, soils, or vegetation. The data source for the energy variables of this study is "World Energy Consumption A Database 1820-2020" (Malanima, 2022), published at Harvard University's Joint Center for History of Economics.[10] This comprehensive database contains primary energy consumption levels from disaggregated sources, covering a wide range of countries.

Before the 1950s, the consumption of clean energy was not significant, and the availability of data for that period was limited. As mentioned earlier, most existing energy literature relies on data from 1965 onwards. However, when employing econometric techniques to estimate break structures accurately in clean energy series, it is crucial to have an earlier start date. This allows for a more precise examination of breaks, particularly to assess the impact of the Suez Crisis in 1957 and the oil crisis of the 1970s.

Using data from 1950 to 2020 in this study provides a suitable time interval for such purposes because our analysis contends that the series of renewable and nuclear energy underwent three major structural changes: the first occurred during the 1970s oil crisis, the second during the implementation and aftermath of the Kyoto Protocol in the 2000s, and the third following the Fukushima Nuclear Disaster in 2011. Figure 3.2.5 shows the level series of renewable energy consumption and nuclear energy consumption for the countries in our study.

In 2020, China achieved the highest renewable energy consumption levels, reaching

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[10] The full dataset is obtained upon request from Professor Malanima.

401 million tons of oil equivalent (mtoe) due to significant efforts to improve the renewables sector, especially over the past 10 years. This amount is nearly double that of the US. Analyzing countries outside this list may not be as insightful because, even for the 10th country, the UK, renewable energy consumption levels are relatively low at 44 mtoe. Nuclear energy consumption levels are even lower, with the highest in the US at 249 mtoe and the lowest in Japan at 3.5 mtoe.

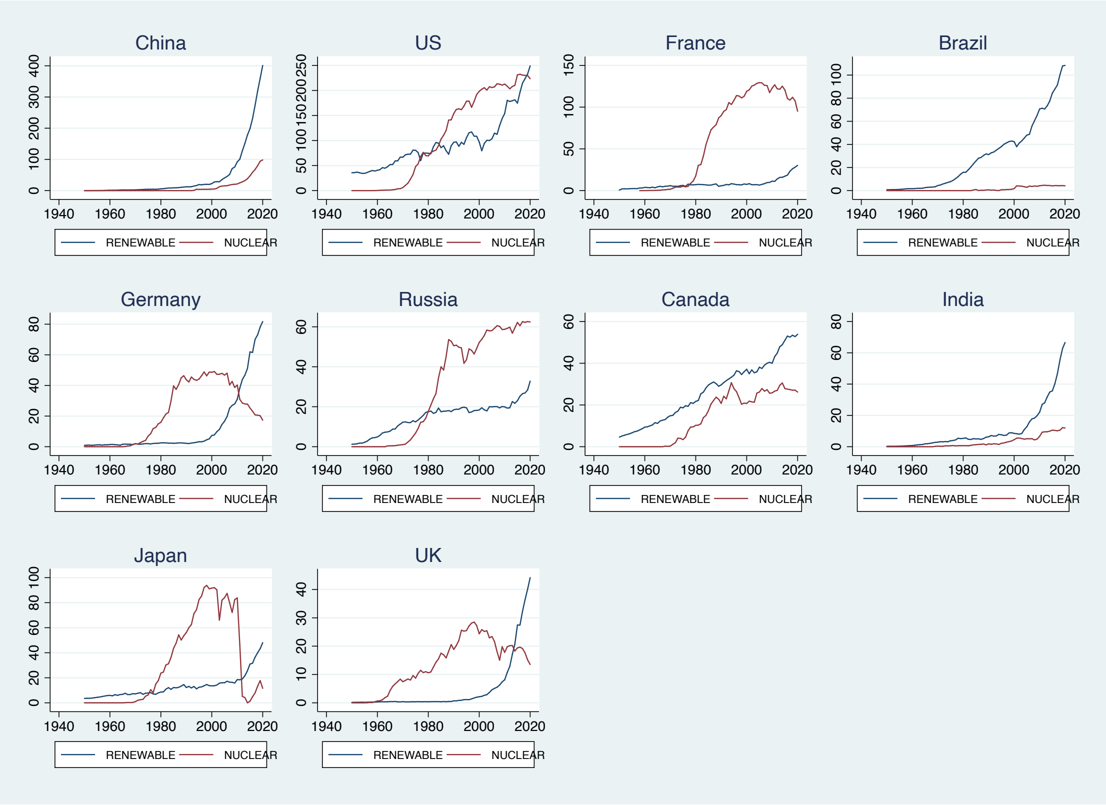


Figure 4.2.1 Renewable Energy and Nuclear Energy Consumption Levels (mtoes)

Figures 4.2.2 and 4.2.3 show joint plots for per capita emissions, per capita GDP, and the share of renewables consumption, as well as per capita emissions, per capita GDP and the share of nuclear energy consumption. All variables have been transformed into natural logarithms for scaling purposes. Interpreting these variables in natural logs rather than levels is preferred, as comparing growth rates can be more plausible and intuitive for these macro indicators.

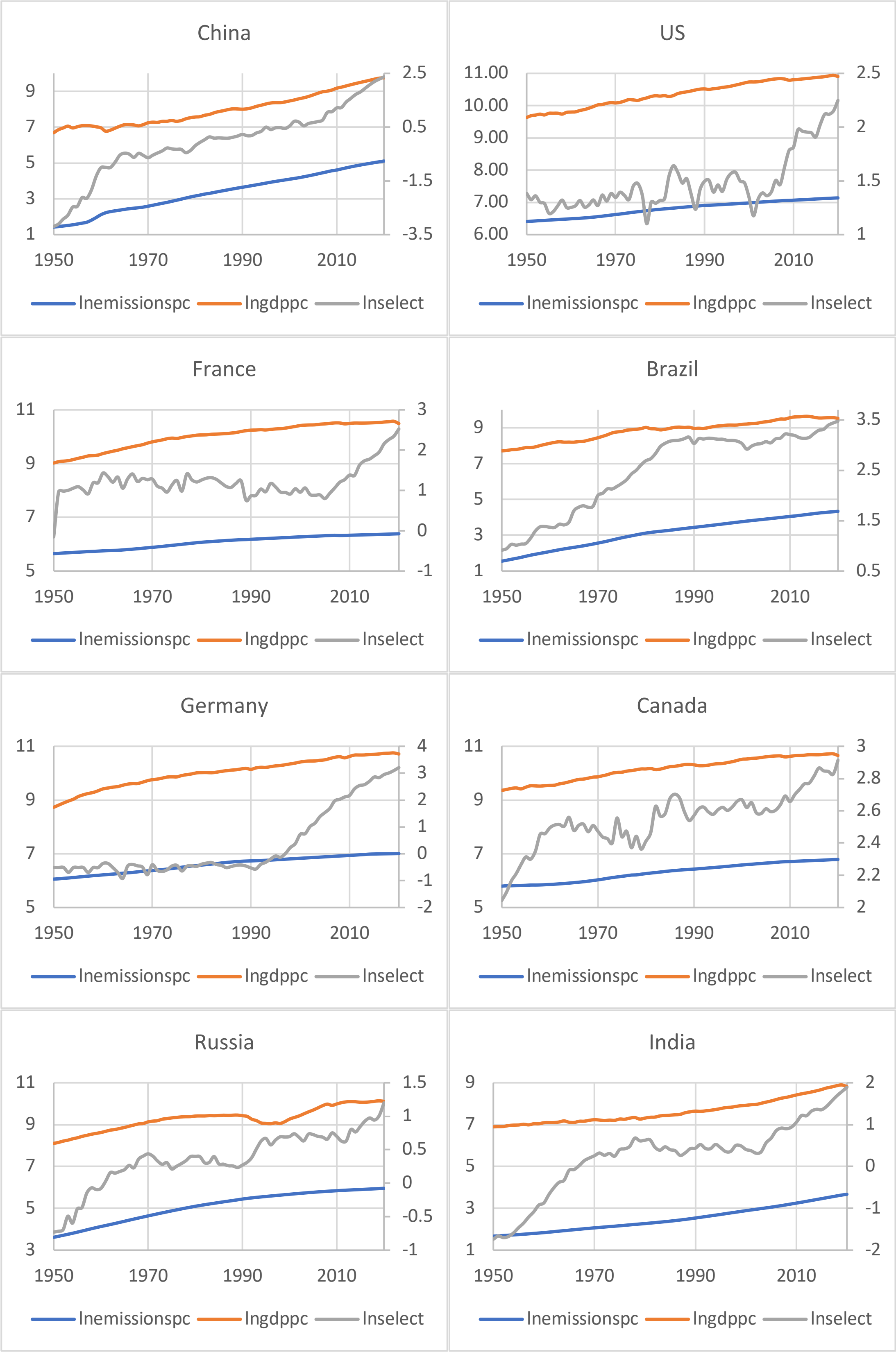
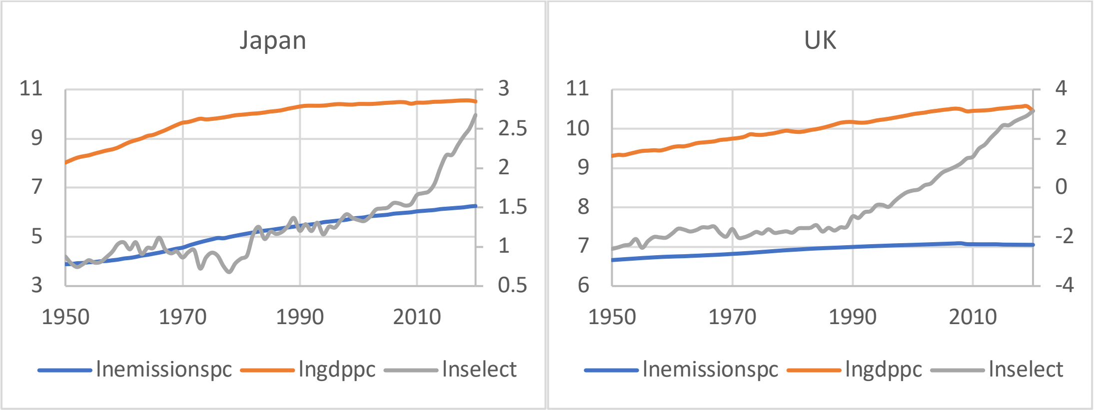


Figure 4.2.2 Joint plot for the per capita emissions, per capita GDP and share of renewables consumption



Left axis is for emissions (million tonnes of CO2 per person) and GDP (USD per person) and the right axis is for share of renewable energy (%).
All variables are in natural logs.

Figure 4.2.2 (continued)

In each plot, the left axis represents emissions and GDP, while the right axis represents shares of renewables and nuclear energy. These plots facilitate the visualization of joint movements between the variables. We observe that the growth of emissions per capita and GDP per capita move almost parallel for all countries, indicating potential cointegration between these variables. However, there is a slight divergence for the US, France, Germany, and the UK, where the growth of per capita emissions is becoming slower compared to the growth of per capita GDP.

We cannot detect a visible break in the emissions and GDP series, except for Russia in the 1990s during the dismantling of the USSR. However, the renewable and nuclear energy series seems to have undergone several structural breaks. The 2000s marked a turning point for renewables in almost all countries due to breakthroughs in addressing climate change. Unlike others, Germany and the UK's renewables sector began to develop early, around the 1990s, possibly because of their heightened environmental awareness or efforts to increase energy sovereignty following the oil crisis. Brazil started its renewable investments even earlier, using renewable energy as a hedge against fossil fuels after the 1970s oil crisis. It is noteworthy that other countries used nuclear energy as a remedy against the oil crisis. We observe high growth rates in the share of nuclear energy following the oil crisis, particularly in Germany, Canada, Russia, and Japan.

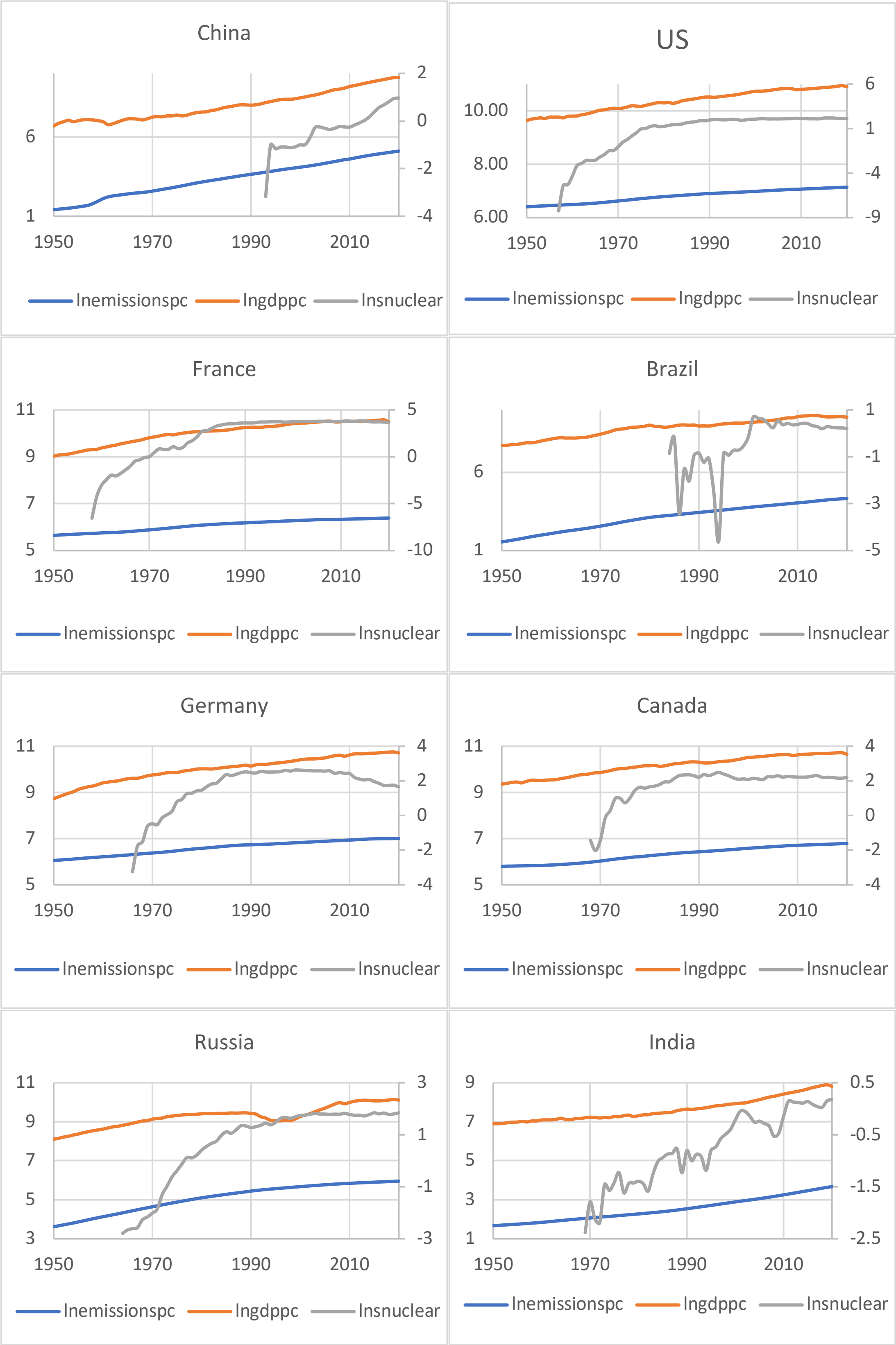
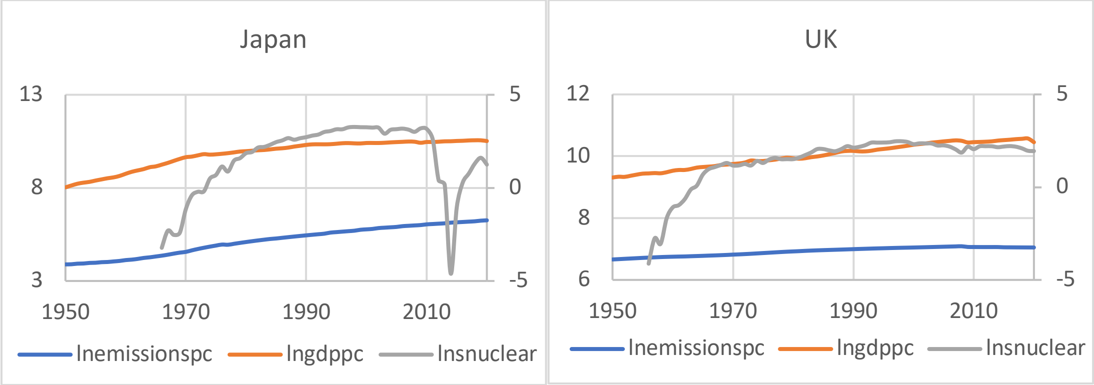


Figure 4.2.3 Joint plot for the per capita emissions, per capita GDP and share of nuclear energy consumption



Left axis is for emissions (million tonnes of CO2 per person) and GDP (USD per person) and the right axis is for share of nuclear energy (%).
All variables are in natural logs.

Figure 4.2.3 (continued)

In the US and France, the share of nuclear energy began to grow following the Suez Crisis in 1957. However, in these two countries, the growth slope of nuclear shares became steeper with the oil crisis. The growth in nuclear energy shares slowed down after the Chernobyl Accident in 1986. Japan saw an all-time low in nuclear energy with the Fukushima Disaster in 2011. In Japan, nuclear energy shares started to pick up after three years, but the growth rate turned negative in 2020.

As a result of Fukushima, we observe slightly negative growth rates in nuclear energy shares in Brazil, Canada, and the UK as well. Germany decided to phase out nuclear energy completely by 2022, although this has been prolonged due to energy shortage concerns because of the war in Ukraine. The US, France, and Russia appear to have halted new investments in the sector but have not shut it down entirely. On the other hand, growth in nuclear energy consumption remains positive for China and India, as these developing countries strive to meet high energy demands during their rapid growth.

Figures 4.2.2 and 4.2.3 clearly show that per capita CO_2 emissions and per capita GDP growth exhibit steadily rising trends, with GDP growing at a faster rate than emissions. The shares of renewables and nuclear energy also appear to be trending upward. This suggests that a linear trend should be included in the relationship between these variables. Additionally, the structural breaks significantly impact the unit root properties and the short- and long-run relationships among the variables. These properties must be considered when building a statistical model using these variables.

Table 4.2.1 Summary Statistics of per capita CO2 Emissions, per capita GDP, Share of Renewables and Share Nuclear Energy

Per capita CO_2 Emissions

lnemissionspc	**# of Observations**	**Mean**	**Std Dev**	**Minimum**	**Maximum**
China	71	3.34	1.08	1.42	5.11
US	71	6.80	0.23	6.40	7.14
France	71	6.07	0.24	5.65	6.39
Brazil	71	3.14	0.82	1.55	4.33
Germany	71	6.60	0.30	6.06	7.01
Canada	71	6.31	0.34	5.79	6.79
Russia	71	5.09	0.72	3.62	5.96
India	71	2.50	0.59	1.67	3.67
Japan	71	5.16	0.77	3.89	6.25
UK	71	6.92	0.13	6.66	7.09

Per capita GDP

lngdppc	**# of Observations**	**Mean**	**Std Dev**	**Minimum**	**Maximum**
China	71	7.97	0.90	6.68	9.75
US	71	10.36	0.40	9.63	10.94
France	71	10.02	0.47	9.02	10.57
Brazil	71	8.84	0.57	7.71	9.64
Germany	71	10.02	0.54	8.73	10.75
Canada	71	10.15	0.43	9.36	10.72
Russia	71	9.27	0.54	8.10	10.14
India	71	7.63	0.58	6.89	8.89
Japan	71	9.85	0.75	8.03	10.56
UK	71	10.02	0.39	9.31	10.57

Share of Renewables

lnselect	**# of Observations**	**Mean**	**Std Dev**	**Minimum**	**Maximum**

Table 4.2.1 (continued)

China	71	-0.06	1.28	-3.20	2.37
US	71	1.48	0.26	1.10	2.25
France	71	1.22	0.39	-0.15	2.53
Brazil	71	2.49	0.80	0.91	3.47
Germany	71	0.32	1.27	-0.92	3.21
Canada	71	2.55	0.17	2.04	2.91
Russia	71	0.36	0.42	-0.73	1.20
India	71	0.26	0.87	-1.74	1.89
Japan	71	1.25	0.45	0.68	2.67
UK	71	-0.73	1.60	-2.49	3.13

Share of Nuclear Energy

lnsnuclear	**# of Observations**	**Mean**	**Std Dev**	**Minimum**	**Maximum**
China	28	-0.37	0.86	-3.17	0.96
US	64	0.64	2.32	-8.24	2.19
France	63	2.08	2.42	-6.54	3.83
Brazil	37	-0.42	1.18	-4.62	0.69
Germany	55	1.66	1.29	-3.24	2.63
Canada	53	1.76	1.00	-2.03	2.50
Russia	57	0.70	1.47	-2.79	1.84
India	52	-0.76	0.69	-2.38	0.18
Japan	55	1.55	1.92	-4.61	3.27
UK	65	1.42	1.39	-4.13	2.47

Emissions are in million tonnes of CO2 per person and GDP is USD per person and share series are in percent (%).

All variables are in natural logs.

Table 4.2.1 presents the descriptive statistics. The variable names for the natural logs of the analyzed indicators are as follows: lnemissionspc for per capita CO_2 emissions, lngdppc for per capita GDP, lnselect for the share of renewable energy consumption in total primary energy consumption, and lnsnuclear for the share of nuclear energy consumption in total primary energy consumption. The dataset includes 71 data points for each country, covering the period from 1950 to 2020 for lnemissionspc, lngdppc, and lnselect variables. Some countries did not have nuclear energy until around the 1960s. Brazil and China adopted nuclear energy even later, in 1984 and 1993, respectively. Consequently, the variable lnsnuclear has a lower number of observations for all country series. We observe that Germany, Brazil, and the UK are significant investors in renewable energy, while France, followed by Japan, has the highest share of nuclear energy.

4.3. Methodology

This section provides a brief review of previous methodologies used to analyze cointegration, with a particular focus on time-varying cointegration (TVC). Among existing procedures to determine cointegration, Johansen's methodology (Johansen, 1995), which forms the base for TVC, and the Bierens and Martins (2010) TVC Test are explained in detail. Finally, we demonstrate how we modeled the long-run relationship between CO_2 emissions and clean energy consumption using TVC.

When dealing with non-stationary time series data, standard regression techniques can lead to spurious results, where relationships appear significant but are actually meaningless. Cointegration helps identify genuine long-term relationships, providing a foundation for reliable modeling and inference. Cointegration between non-stationary variables specifies a long-term stationary relationship between those variables. To find cointegration, we look for a stationary linear combination of non-stationary variables. For a bivariate relationship with two non-stationary variables $y_t \sim I(1)$ and $x_t \sim I(1)$, the linear combination of these variables can be represented as:

$$y_t = \beta x_t + u_t \qquad (4.3.1)$$

If the linear combination with the cointegrating vector $[1 \quad -\beta]$ is stationary, the residuals from this regression are also stationary. The first procedure for testing cointegration, the Engel and Granger Cointegration Test (1987), finds $\hat{u}_t$ as the estimate of the residuals of the above regression and uses the ADF Unit root test with estimated t-statistics from the DF test by Monte-Carlo simulations under the unit root null. If the $\hat{u}_t$ series is stationary, cointegration is defined by the $[1 \quad -\beta]$ cointegrating vector; otherwise, the regression is spurious.

Most macroeconomic series are represented by multivariate relationships. The literature on cointegration also focuses on this case. In the multivariate case, y_t is a

$kx1$ vector of $I(1)$ variables, and there exists a $kx1$ vector β such that $\beta' y_t$ is $I(0)$. Then, y_t is said to be cointegrated of order 1 where the parameters of the vector β are the parameters of the cointegrating equation. For a vector y_t of length k there may be at most $k - 1$ cointegrating vectors.

The Engle-Granger Test estimates only one cointegrating vector, even when testing for cointegration between more than two variables. The low power of residual-based tests is due to ignoring equation dynamics and concentrating on error dynamics. There is and error correction representation for every cointegration relationship (Maddala and Kim, 1998). Kremers et al. (1992) suggests using error correction methodologies that allow for both equation and error dynamics, considering short- and long-term relationships between variables in a multivariate equation and estimating a vector of error terms. Methodologies should consider the real-life relationships between economic variables, modeling the regression equation also by addressing misspecifications due to endogeneity.

Johansen's maximum likelihood (ML) procedure tests how many cointegrating vectors there are in a multivariate framework (Johansen, 1995). Johansen uses the Vector Error Correction Model (VECM), which shows how variables adjust in the short term to return to equilibrium in the long term. The Johansen VECM is represented as:

$$\Delta y_t = \alpha\beta' y_{t-1} + \sum_{i=1}^{p-1} \Gamma_i \Delta y_{t-i} + v + \delta t + e_t \tag{4.3.2}$$

Here, y_t is a $kx1$ vector of variables. $\alpha\beta'$, also denoted as Π, contains information about the long-term relationship among the variables. α is the matrix of adjustment coefficients, and β' is a kxk matrix of cointegrating vectors. The number of cointegrating vectors is determined by $rank(\beta) = r$, where $r \leq k$. The VECM equation is in differences, with v representing a linear time trend while δt representing a quadratic time trend in levels (Baum and Hurn, 2021).

The VECM in equation 4.3.2 can be rewritten in a more general form as:

$$\Delta y_t = \alpha(\beta' y_{t-1} + \mu + \rho t) + \sum_{i=1}^{p-1} \Gamma'_i \Delta y_{t-i} + v + \delta t + e_t \tag{4.3.3}$$

Equation 4.3.3 allows testing for stationary cointegrating relationships around a constant mean and/or around a time trend. Specifying the VECM with constants and trends requires a combination of theory and graphical analysis of the data before proceeding with the analysis (Baum and Hurn, 2021).

Johansen's algorithm solves an eigenvalue problem for the matrix β to find the number of cointegrating vectors, choosing the ones with eigenvalues significantly different from zero. All the parameters for the dynamic relations of the VECM (adjustment parameter (α), parameters of the cointegrating equation (β') and the short-run parameters (Γ'_i)) are estimated simultaneously by maximum likelihood. The vector of the disturbances, e_t is assumed to be normally distributed with a null mean vector and covariance matrix V. Based on these assumptions, the log-likelihood function for a sample of T observations is presented as:

$$LL = -\frac{T}{2}\, ln(2\pi) - \frac{\mathrm{T}}{2} ln|V| - \frac{1}{2(T-p)} \sum_{t=p+1}^{T} e'_t V^{-1} e_t$$

In Johansen's Test for cointegration, the idea behind rejection is that, according to the LR test statistics, if the log-likelihood of the unconstrained model (including the cointegrating equations) is significantly higher than that of the constrained model (excluding the cointegrating equations), we reject the null hypothesis of no cointegration (Baum and Hurn, 2021). Johansen's Methodology consists of two tests:

1. Trace Test:
   - Null hypotheses: $H_0{}^0: r = 0, H_0{}^1: r = 1, H_0{}^2:\ r = 2, \ldots$
   - Alternative hypotheses: $H_1{}^0: r > 0, H_1{}^1:\ r > 1, H_1{}^2: r > 2, \ldots$
   - LR Test statistic: $LR = -T \sum_{i=r_0+r}^{k} \ln{(1-\hat{\lambda}_i)}$

where $\hat{\lambda}_i$'s are eigenvalues of the matrix β' for the alternative hypothesis. Trace Test tests the alternative hypothesis in a sequential manner until the test statistic cannot reject the null hypothesis. The test is suggested for small samples.

2. Maximum Eigenvalue Test:
   - Null hypotheses: $H_0{}^0: r = 0, H_0{}^1: r = 1, H_0{}^2:\ r = 2, \ldots$
   - Alternative hypotheses: $H_1{}^0: r = 1, H_1{}^1:\ r = 2, H_1{}^2: r = 3, \ldots$

- LR Test statistic: $LR = -T \, ln \, (1 - \hat{\lambda}_{r_0+1})$

where $\hat{\lambda}_{r_0+1}$ is the eigenvalue of the β' for the alternative hypothesis. The test is suggested for large samples.

In Johansen's standard approach, it is assumed that the cointegrating vector is constant over time. This assumption may be restrictive due to changes in taste, technology, or economic policies. Structural changes invalidate standard testing procedures as the VEC model is no longer linear in parameters. This poses a problem since most cointegration tests cannot discriminate between cointegration with structural changes and the absence of cointegration. Some studies integrate time-varying properties of the relations between variables into their analysis (Apergis and Payne, 2014; Baum and Hurn, 2021).

Gregory and Hansen (1996) methodology looks for cointegration in the presence of sharp breaks under the long-run equation. Hatemi-J (2008) and Maki (2012) expands Gregory and Hansen (1996) methodology to allow for two breaks and multiple unknown breaks, respectively. Westerlund (2006) introduces a panel cointegration test with structural breaks based on Gregory and Hansen's test. We do not detail these the cointegration tests with sharp breaks here. Appendix A provides technical information on these tests.

Structural changes in the time series variables may involve smooth changes instead of sharp ones. Fourier ADL (Autoregressive Distributed Lag) cointegration test of Banerjee et al. (2017) considers smooth structural breaks in the VECM:

$$\Delta y_{1t} = \beta'_1 y_{1t-1} + \beta'_2 y_{2t-1} + \sum_{i=1}^{p-1} \Gamma'_i \Delta y_{2t-i} + d(t) + e_t \tag{4.3.4}$$

where y_{1t} is a uni-variate process and $d(t)$ is the deterministic term involving smooth changes:

$$d(t) = \alpha_0 + \sum_{k=1}^{n} \lambda_k \sin\left(\frac{2\pi kt}{T}\right) + \sum_{k=1}^{n} \gamma_k \cos\left(\frac{2\pi kt}{T}\right)$$

k is the appropriate Fourier Frequency, and lag lengths are determined by AIC.

The methodology tests:

H_0: $\beta_1 = 0$ (no CI) vs H_1: $\beta_1 < 0$ (CI).

If t-statistic for β_1 from the regression is less than Fourier ADL critical values, the null hypothesis is rejected in favor of the existence of cointegration.

Introducing sharp and smooth breaks to the constant and trend parameters in the VECM regressions, as in Fourier ADL, allows for the breaks only in the deterministic terms, providing an idea for the structural changes in the relationship. However, in a multivariate framework, the impact of a break that occurred in one variable may occur at a different date or structure for another variable (Maddala and Kim, 1998). Thus, methods involving determining the breaks in the deterministic term may not be the best approach to tackle the issue of structural breaks in the cointegration relationship.

The methodologies mentioned above leave the question of whether the cointegration parameters are changing, unanswered. Gregory and Hansen (1996) and Maki (2012) methodologies, allowing for sharp regime breaks in the parameters of the long-run equation, partly address this issue. Park and Hahn (1999) apply the Time-Varying Cointegration Parameters idea with smooth breaks. Their initial long-run model is:

$$y_t = \beta_t x_t + e_t \tag{4.3.1}$$

$$\beta_t = \beta\left(\frac{t}{T}\right)$$

where β is a smooth function such that;

$$\beta_{pq}(r) = \alpha_0 + \sum_{j=1}^{p} \alpha_1 r^j + \sum_{j=1}^{p} (\alpha_{p+2j-1}, \alpha_{p+2j} \phi_j(r))$$

$$\phi_j(r) = (\cos 2\pi jr, sin 2\pi jr) \; for \; r \in [0,1]$$

e_t and Δx_t are stationary.[11]

Similar to Park and Hahn Test with Time-Varying Parameters, Bierens and Martins (2010) incorporate smooth forms into the parameters but build their model upon Johansen's approach (1995). Bierens and Martins (2010) introduce a time-varying VECM in which the cointegrating vector parameters are smooth functions of time. The main advantage of Bierens and Martins' approach is that, unlike Park and Hahn Test,

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[11] To yield efficient and optimal estimators, Park and Hahn (1999) transform y_t and x_t to a stationary system using the stationary components of the model by Canonical Cointegration Regression, which we will not detail here.

it is rooted within Johansen's technique, making it easier to relate to the intuition behind the approach while expanding the previously used technique. Its advantage over Gregory and Hansen (1996) and Maki (2012) methodologies is that Bierens and Martins' Test estimates the long-run parameters using the entire time span of data, not subsamples divided by break dates.

4.3.1. Bierens and Martins' TVC Test

In the Bierens and Martins (2010) method, the main distinction from Johansen's technique is the introduction of a time-varying β. The adjustment parameter α remains the same. Additionally, they modify the VECM in equation 4.3.2 for the drift case only, where $\delta t = 0$. They claim that most of the macroeconomic time series, y_t, are non-zero mean first difference stationary and the long-run relations are non-zero mean stationary, meaning Δy_t and $\beta'_t y_t$ are stationary and v is non-zero. The resulting VECM is:

$$\Delta y_t = \alpha\beta'_t y_{t-1} + \sum_{i=1}^{p-1} \Gamma'_i \Delta y_{t-i} + v + e_t \qquad (4.3.5)$$

when the long-run cointegrating relation is constructed as:

$$\beta'_t y_t = e_t \qquad (4.3.6)$$

e_t represents the short-run deviations from the long-run relation.

The time variation of β_t is provided by Chebyshev time polynomials, $P_{i,T}(t)$.

$P_{0,T}(t) = 1$

$P_{i,T}(t) = \sqrt{2}\cos\left(\frac{i\pi(t-0.5)}{T}\right)$

for $t = 1, \dots, T$ and $i = 1,2,3, \dots$

For all i and j:

$\frac{1}{T}\sum_{t=1}^{T} P_{i,T}(t)P_{j,T}(t) = 1 \, for \; i = j$

ensures orthonormality, so that any function $g(t)$ of discrete time t can be represented by:

$g(t) = \sum_{i=0}^{T-1} \xi_{i,T} P_{i,T}(t)$

where

$\xi_{i,T} = \frac{1}{T}\sum_{t=1}^{T} g(t)P_{i,T}(t)$.

$g_{m,T}(t) = \sum_{i=0}^{m} \xi_{i,T} P_{i,T}(t)$ for $m < T - 1$

Thus, β can be approximated as;
$\beta_t = \beta_m(t/T) = \sum_{i=0}^{m} \xi_{i,T} P_{i,T}(t)$.
$\xi_{i,T} P_{i,T}(t)$ are the parameters of decreasing smoothness provided by Fourier components. m is the order of Chebyshev's polynomials determining the length and width of the oscillations of the time-varying parameter equations. If $m = 0$, $\beta_t = \xi_{0,T}$ is a constant matrix, equivalent to Johansen's time invariant cointegration case as the null hypothesis.

The log-likelihood function with m is then stated as:
$LL\ (r, m) = -\frac{T}{2} ln(2\pi) - \frac{T}{2} ln|V| - \frac{T}{2} \sum_{j=1}^{r} ln(1 - \hat{\lambda}_{m,j})$
where $\hat{\lambda}_{m,j}$ are the estimates of the eigenvalues. The likelihood ratio (LR) test statistic for the null hypothesis $m = 0$ and the alternative hypothesis $m = \hat{m}$ is estimated as:
$LR_T^{TVC} = -T \sum_{i=1}^{r} \left[\ln\left(1 - \hat{\lambda}_{m,i}\right) - \ln\left(1 - \hat{\lambda}_{0,i}\right) \right]$

As $T \to \infty$, LR_T^{TVC} test statistic has a χ^2_{rmk} distribution. The optimal choice of m is comparable to the optimal choice of lag order of an auto-regressive process. Therefore, they suggest using Hannan-Quinn (1979) or Schwarz (1978) information criteria (HQC and SBC, respectively) for choosing the order of Chebyshev's polynomials:
$HQC(p) = -2\ln(LL) + 2m\ ln(\ln(N))$
$SBC(p) = -2\ln(LL) + m\ ln(\mathrm{N})$
where LL is the maximum likelihood for the chosen m. Then, m gives the minimum value for any criterion of choice that determines the model.

In Johansen's methodology, cointegrating vector parameters are estimated by normalizing the cointegration relationship by the most endogenous variable. This provides ease of interpretation. However, Bierens and Martins (2010) do not perform any normalization to allow all cointegrating parameters to vary. Analysts need to be careful while interpreting the estimated long-run relationships, observing the changing patterns of all parameters together. Bierens and Martins (2010) provide plots for the changing long-run parameters, allowing for visual inspections.

Cointegration is a purely statistical concept, and the cointegrating vectors need not have any economic meaning. However, Johansen and Juselius (1994) propose that after empirical identification of the model with long-run and short-run parameters, economic identification should be considered to interpret the estimated coefficients and empirically identified structure (Maddala and Kim, 1998). To incorporate time-varying cointegration into the relationship between CO_2 emissions and clean energy consumption, we follow Bierens and Martins' methodology. Here,

$y_t = (lnemissionspc, lngdppc, lnselect)$

constitutes the vector of variables for the renewables equation, while,

$y_t = (lnemissionspc, lngdppc, lnsnuclear)$

is the vector for the nuclear energy equation looking for the long-run relationships of interest.

The time-varying parameters are estimated for the VECM in Equation 4.3.5. Then, for the cases where we found evidence for cointegration, we use Equation 4.3.6:

$$\beta_{\mathrm{t,lnemissionspc}}\mathrm{lnemissionspc} + \beta_{\mathrm{t,lngdppc}}\mathrm{lngdppc} + \beta_{\mathrm{t,lnselect}}\mathrm{lnselect} = e_t$$

and

$$\beta_{\mathrm{t,lnemissionspc}}\mathrm{lnemissionspc} + \beta_{\mathrm{t,lngdppc}}\mathrm{lngdppc} + \beta_{\mathrm{t,lnsnuclear}}\mathrm{lnsnuclear} = e_t$$

along with the plots of the time-varying parameters for interpretation of the long-run relations.

4.4. Empirical Results

Augmented Dickey-Fuller (ADF) tests have been conducted on the levels and first differences of each series to assess if the variables are I(0) or I(1). The results for the level series are shown in Table 4.4.1. The ADF test does not reject the null hypothesis of a unit root at any level, except for the share of nuclear energy series in Brazil, Canada, and the UK. In the literature, most macroeconomic variables and energy indicators are shown to be I(1). Therefore, we may continue the cointegration analysis by concluding the series are I(1). The lags for the ADF test are determined by Ng and Perron's methodology (Ng and Perron, 2001). We claim that the level of emissions results from industrial production and efforts to mitigate emissions. In this study, GDP per capita is taken as the measure of economic growth, representing the demand side effects on emissions. The share of clean energy consumption is taken as the measure of mitigation efforts, representing the supply side effects.

Table 4.4.1 Conventional Unit Root Tests for the level series

Per capita CO_2 Emissions

	China	**US**	**France**	**Brazil**	**Germany**	**Russia**	**Canada**	**India**	**Japan**	**UK**
ADF on Levels										
Lags	3	2	3	4	3	3	4	2	2	3
Has a unit root with Trend and Intercept	-3.153	-1.448	-1.176	-0.970	-0.102	-1.422	-2.180	-1.730	-2.432	0.972
Integration Order	I (1)	I (1)	I (1)	I (1)	I (1)	I (1)	I (1)	I (1)	I (1)	I (1)

Per capita GDP

	China	**US**	**France**	**Brazil**	**Germany**	**Russia**	**Canada**	**India**	**Japan**	**UK**
ADF on Levels										
Lags	4	1	2	2	5	3	1	1	2	2
Has a unit root with Trend and Intercept	-1.556	-0.791	0.135	-1.648	-2.515	-2.867	-0.227	-0.529	-1.00	0.603
Integration Order	I (1)	I (1)	I (1)	I (1)	I (1)	I (1)	I (1)	I (1)	I (1)	I (1)

Reject the null hypothesis with: *** p<0.01, ** p<0.05, * p<0.1
Reject the null hypothesis with: *** LM>0.01 critical value, ** LM>0.05 critical value, *LM>0.1 critical value
DFGLS gives unit root for the level series of I(0) variables, stationarity for the first differences of I(1) variables.
All series are log-transformed.

Table 4.4.1 (continued)

Share of Renewables										
	China	**US**	**France**	**Brazil**	**Germany**	**Russia**	**Canada**	**India**	**Japan**	**UK**
ADF on Levels										
Lags	2	1	2	1	1	1	2	1	1	1
Has a unit root with Trend and Intercept	-2.814	-1.585	0.627	-1.106	-0.550	-2.879	-3.050	-1.704	0.564	0.629
Integration Order	I (1)	I (1)	I (1)	I (1)	I (1)	I (1)	I (1)	I (1)	I (1)	I (1)
Share of Nuclear Energy										
	China	**US**	**France**	**Brazil**	**Germany**	**Russia**	**Canada**	**India**	**Japan**	**UK**
ADF on Levels										
Lags	2	4	1	1	2	1	1	1	1	1
Has a unit root with Trend and Intercept	-2.996	-2.664	-1.690	-3.354*	-4.098	-1.596	-7.451***	-3.034	-2.132	-5.897***
Integration Order	I (1)	I (1)	I (1)	I (0)	I (1)	I (1)	I (0)	I (1)	I (1)	I (0)

Reject the null hypothesis with: *** p<0.01, ** p<0.05, * p<0.1

Reject the null hypothesis with: *** LM>0.01 critical value, ** LM>0.05 critical value, *LM>0.1 critical value

DFGLS gives unit root for the level series of I(0) variables, stationarity for the first differences of I(1) variables.

All series are log-transformed.

We first apply Johansen’s Trace test of cointegration without considering the existence of structural changes. The results are presented in Table 4.4.2. Johansen’s Test could not detect any cointegration vector for the US and Brazil in the renewable energy equation and for Russia and India in the nuclear energy equation. For the other country series, Johansen’s test finds either one or two cointegration (CI) vectors. For some countries, we found two CI vectors. The nuclear energy relation for Canada and the UK was expected to have more than one CI vector because the nuclear shares series are I(0) for these countries.

Table 4.4.2 Johansen’s Trace Test Results

Model	**lnemissionspc~lngdppc~lnselect**				**lnemissionspc~lngdppc~lnsnuclear**			
	Lags	**# of CI Vectors**	**Trace stat.**	**5% CV**	**Lags**	**# of CI Vectors**	**Trace stat.**	**5% CV**
China	2	2	0.289	4.68	2	1	16.922	25.32
US	2	0	33.429	42.44	2	2	9.873	12.25
France	2	2	5.584	12.25	2	1	24.13	25.32
Brazil	2	0	28.922	42.44	2	1	19.768	25.32
Germany	2	1	23.217	25.32	2	2	10.99	12.25
Russia	2	1	19.757	25.32	2	0	31.342	42.44
Canada	2	1	15.572	25.32	2	2	10.872	12.25
India	2	1	19.90	25.32	2	0	35.583	42.44
Japan	2	2	4.814	12.25	2	1	21.579	25.32
UK	2	1	17.434	25.32	2	2	6.857	12.25

Null hypothesis of (r-1) CI vectors is rejected at 5% level.
Number of lags are chosen according to AIC.

The resulting parameters for the VECM of the Johansen’s Test are given in Tables 4.4.3 and 4.4.4. In Johansen’s methodology, the long-run parameter for per capita emissions is normalized to 1. Table 4.4.3 shows that the parameter value for the share of renewables is very low for all countries. While the long-run elasticities of per capita emissions and the share of renewables are negative for most countries, the elasticities for India and the UK are positive. For Germany, Russia, Canada, and Japan, the impact of the share of renewables is not significant at the 5% level. For China, the US, France, and Brazil, per capita emissions and the share of renewables are found to be negatively related in the long run. All adjustment parameters for Russia and Japan have the same signs. With the Time Invariant Cointegration analysis, it is found that these countries may not reach long-run equilibrium with the resulting adjustments to short-run deviations.

Table 4.4.3 Cointegration Relations: lnemissionspc~lngdppc~lnselect

		CI Vector Parameters		**Adjustment parameter: alpha**		
		lngdppc	**lnselect**	**dlnemissionspc eqn**	**dlngdppc eqn**	**dlnselect eqn**
China	Parameter value	.163	-.099	-.231	.259	-.487
	Z-stat	*- 4.89 ****	*-6.70****	*-6.46 ****	*1.60 ***	*-1.23*
US	Parameter value					
	Z-stat					
France	Parameter value	-.987	-.094	-.024	-.031	.651
	Z-stat	-6.05 ***	-1.96**	-4.80 ***	-0.90	2.52**
Brazil	Parameter value					
	Z-stat					
Germany	Parameter value	3.668	.024	-.001	-.021	.101
	Z-stat	- 3.35***	0.18 *	-3.89***	-5.01***	3.76***
Russia	Parameter value	.435	.080	-.002	-.051	-.197
	Z-stat	2.20**	0.33	-2.87 ***	-1.90**	-3.82***
Canada	Parameter value	-.966	-.141	-.045	.142	.385
	Z-stat	- 7.55***	-1.72*	-3.71***	2.01**	2.48**
India	Parameter value	-.471	.034	-.042	.212	.669
	Z-stat	-18.69***	3.86***	-4.65***	0.99	1.10
Japan	Parameter value	-.345	.084	-.023	-.363	-.081
	Z-stat	-6.53 ***	- 1.53 *	-2.72***	-4.86 ***	-0.26
UK	Parameter value	-.096	.064	-.100	-.233	1.895
	Z-stat	-0.80	7.50***	-5.82***	-1.85*	2.51**

Reject the null hypothesis with: *** $p<0.01$, ** $p<0.05$, * $p<0.1$

Adjustment to equilibrium is led by emissions for India and by GDP for China and Japan. For all other country series, the share of renewables leads the adjustment. These countries had to increase their renewable consumption rapidly in recent years, compared to their slowing economic growth rates. This may have resulted in the dominance of the share of renewables in the short-run analysis.

Table 4.4.4 Cointegration Relations: lnemissionspc~lngdppc~lnsnuclear

		CI Vector Parameters		**Adjustment parameter: alpha**		
		lngdppc	**lnsnuclear**	**dlnemissionspc eqn**	**dlngdppc eqn**	**dlnsnuclear eqn**
China	Parameter value	-.431	*.019*	-.237	1.928	2.326
	Z-stat	*-16.17****	*2.54****	-1.69*	4.96***	0.69
US	Parameter value	-.120	-.049	.004	-.053	5.039
	Z-stat	-1.20	-9.78***	0.77	-0.63	8.42***
France	Parameter value	-.402	-.012	-.082	-.093	.084
	Z-stat	-3.22 ***	-1.24	-5.13***	-0.87	0.10
Brazil	Parameter value	.073	-.007	.118	-.207	140.95
	Z-stat	6.03***	-7.36***	1.22	-0.19	5.68***
Germany	Parameter value	-2.243	-.077	.001	.100	1.494
	Z-stat	-5.04***	-6.42***	0.32	2.44**	7.00***
Russia	Parameter value					
	Z-stat					
Canada	Parameter value	-.284	-.095	.040	.075	2.937
	Z-stat	-1.69*	-9.36***	3.71***	1.27	7.53***
India	Parameter value					
	Z-stat					
Japan	Parameter value	-.281	.0034	*-.0347*	-.304	-2.913
	Z-stat	*-2.54***	*0.43*	*-3.82 ****	*-3.91****	*-0.82*
UK	Parameter value	-.538	-.051	.007	.065	2.669
	Z-stat	-2.87***	-4.69***	0.95	1.35*	8.27***

Reject the null hypothesis with: *** p<0.01, ** p<0.05, * p<0.1

In Table 4.4.4 it is decpited that the long-run impact of the share of nuclear energy consumption on emissions growth is negative and significant for most countries, except for China and Japan. This means that even if the long-run parameter is very low, growth in the share of nuclear energy results in a decline in the growth of per capita emissions. $\beta_{\text{lnsnuclear}}$ is positive but insignificant for China and Japan. There is no significant cointegration (CI) vector for Russia and India, thus, VECM estimations are not conducted for these countries.

Before applying the Bierens and Martins Test for TVC, which accounts for the smooth regime changes in CI parameters, we first search for evidence of sudden changes in CI parameters using the Gregory-Hansen test for TVC. In cases where we did not find evidence for regime changes, we examined level or trend changes in the CI relationship. Table 4.4.5 presents the results for Gregory-Hansen test. We found that structural changes following the 1970s oil crisis and the subsequent oil glut around the 1980s are significant breaks for the long-run relationship between emissions, GDP, and the share of clean energy series. Regime change is significant for the share of renewables equation in Russia, Canada, Japan, and the UK, and for the share of nuclear energy equation in the US, Germany, and Russia.

Table 4.4.5 Gregory-Hansen Test Results

Model	**lnemissionspc~lngdppc~lnselect**				**lnemissionspc~lngdppc~lnsnuclear**			
	Break Type	**Break Date**	**Test Statistic**	**CI**	**Break Type**	**Break Date**	**Test Statistic**	**CI**
China	Trend	1977	-5.30**	Yes	Regime&trend	1961	-4.44	No
US	Level	1976	-4.83*	Yes	Regime&trend	1972	-5.53*	Yes
France	Regime&trend	1976	-3.96	No	Regime&trend	1964	-4.78	No
Brazil	Trend	2006	-5.04*	Yes	Regime&trend	1966	-5.07	No
Germany	Regime&trend	1982	-4.11	No	Regime	1967	-5.27*	Yes
Russia	Regime&trend	1999	-5.84*	Yes	Regime&trend	1978	-6.29**	Yes
Canada	Regime&trend	1982	-5.84*	Yes	Regime&trend	1971	-4.27	No
India	Regime&trend	2013	-3.62	No	Level	1989	-4.37*	Yes
Japan	Regime&trend	1974	-6.83***	Yes	Regime&trend	1991	-3.59	No
UK	Regime&trend	1975	-5.39*	Yes	Regime&trend	1970	-4.80	No

CI: No means null of no CI cannot be rejected with any break type. Then the estimated insignificant break date is given allowing for breaks in regime, trend, and level.

The Gregory-Hansen test identifies cointegration for the cases where the Johansen Test did not, with a level break in the CI relationship in the US, trend break in Brazil for the renewable energy equations, and a regime break in Russia and a level break in India for the nuclear energy equations. This might seem an improvement towards identifying cointegration. However, the literature argues that determining break dates, especially in the level and/or trend, and incorporating them into a VAR framework is complicated. This complexity is heightened in a VECM framework since we are dealing with non-stationary variables. While most sharp break detection methods assume stationarity between break dates, the impact of a break in one variable may occur at a different date for another variable, further challenging this piecewise stationarity assumption.The Gregory-Hansen test could not capture the expected break dates in the CI relationship, possibly because there are multiple breaks and both sharp and smooth breaks in the long-run equilibrium relationship. There is limited evidence of the most significant events of the period, such as climate change mitigation efforts beginning with the Kyoto Protocol around the 2000s and the Fukushima Disaster in Japan in 2011. If the breaks are not modeled carefully, the resulting analysis cannot be considered reliable.

When assuming Time-Invariant Cointegration and following up with VECM causality tests, we could not reach plausible results for most countries. For example, the empirical results in Table 4.4.3 shows that, Germany, known for its strong compliance with international climate treaties and significant increases in renewable energy shares, shows an insignificant long-run relationship between emissions and the share of renewables. When considering Time-Varying Cointegration with one sharp structural break, results in Table 4.4.5 indicates that two countries with a strong focus on the clean energy sector, Germany again did not show any significant long-run relationship between emissions and the share of renewables, and France's emissions did not have cointegration with any clean energy resources. We argue that the time-varying properties of the CI relationship should be taken into account, unlike Johansen's Test. Moreover, the break dates identified by the Gregory-Hansen test are not plausible. We likely need more breaks or smooth breaks, as these tests do not allow for sensible inferences. Time-Varying Cointegration methodologies that can mimic the variation in parameters are necessary.

The results for Bierens and Martins' TVC Test are presented in Table 4.4.6. Chebyshev's polynomials represent smooth regime changes in the CI relationship. The introduction of Chebyshev's polynomials on the betas of the CI vector supports TVC for any order m. The test statistics are reported only for the m chosen by HQC. We conclude that the long-run the elasticities of relationship between both per capita emissions and the share of renewables, and per capita emissions and the share of nuclear energy are time-varying. The betas of the CI vector change over time due to developments such as new technology, policies, and changes consumers behavior.

Table 4.4.6 Time-Varying Cointegration Test Results

VECM		**lnselect eqn**		**lnsnuclear eqn**
Country	***Order of Chebychev's Polynomials***	**Test Statistics**	***Order of Chebychev's Polynomials***	**Test Statistics**
China	m=7	100.76***	m=3	78.15***
US	m=7	84.55***	m=6	96.19***
France	m=7	90.73***	m=5	85.86***
Brazil	m=6	91.25***	m=4	60.63***
Germany	m=6	77.49***	m=4	63.47***
Russia	m=7	91.44***	m=6	126.90***
Canada	m=5	67.52***	m=5	91.62***
India	m=5	79.60***	m=3	74.73***
Japan	m=5	63.74***	m=4	56.09***
UK	m=7	95.88**	m=6	96.30***

Reject the null hypothesis of time invariant CI alternative to time-varying CI with: *** $p<0.01$, ** $p<0.05$, * $p<0.1$
Lag length is selected as p=2.
Order of Chebyshev's polynomials (m) is selected by HQC following Bierens and Martins (2010).

Unlike Johansen's methodology, Bierens and Martins (2010) do not perform any normalization on the long-run parameters, allowing all CI parameters to vary. The changes in all the estimated parameters are illustrated in Figure 4.4.1 for the renewables equation and Figure 4.4.2 for the nuclear energy equation. The β values in Figures 4.4.1 and 4.4.2 are presented according to the equation:

$$\beta'_t y_t = e_t$$

where $y_t = (\text{lnemissionspc}, \text{lngdppc}, \text{lnselect})$.

Then, for ease of interpretation we arrange the long-run relation as:
$\beta_{\mathrm{lnemissionspc}}\mathrm{lnemissionspc} = \beta_{\mathrm{lngdppc}}\mathrm{lngdppc} + \beta_{\mathrm{lnselect}}\mathrm{lnselect}+e_t$
e_t represents the short-run deviations from the long-run cointegration relation.[12]

In this framework, when interpreting the cointegration relations with time-varying coefficients, we focus on the signs of the coefficients. If the coefficients of lngdppc, lnselect or lnsnuclear and the coefficient of lnemissionspc are of same sign, a decrease in one of the three predictor variables will result in a decrease in per capita emissions growth. If the coefficients have opposite signs, an increase in one of the three predictor variables will result in a decrease in the per capita emissions growth.

Hypothetically, if clean energy lowers emissions in the long run, the parameters of the clean energy variables are expected to be in the opposite direction with $\beta_{\mathrm{t,lnemissionspc}}$. However, the literature cannot give an exact answer because clean energy consumption may lower emissions, but the more plausible result may be that it will increase emissions less. This is partly because of the emissions created by solar panel or wind turbine production and partly because clean energy consumption remains limited compared to conventional energy. Here, using the share of clean energy as a variable will lead to better results. There is a higher possibility that higher clean energy shares will result in lower emissions. From another perspective, increasing emissions may result in higher clean energy shares as policies are applied to promote less harmful energy production techniques. Under the economic identification framework, this second mechanism may be seen as a short-run adjustment responding to timely emissions policies rather than a long-run relationship.

For the $lnemissions{\sim}lngdppc$ relation, if the EKC hypotheses hold, it is expected that when $\beta_{\mathrm{t,lnemissionspc}} > 0$, $\beta_{\mathrm{t,lngdppc}} < 0$ and vice versa for the developed countries. For developing countries $\beta_{\mathrm{t,lnemissionspc}}$ and $\beta_{\mathrm{t,lngdppc}}$ should have the same sign. Figure 4.4.1 presents the time-varying parameters for the renewables equation, while Figure 4.4.2 presents the time-varying parameters for the nuclear energy

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[12] We have provided the the fitted values and residuals of the estimation results for renewables equation of The US as an example for better understanding.

equation. In Figures 4.4.1 and 4.4.2, we can observe that $\beta_{\mathrm{lnemissionspc}}$ is usually more volatile than β_{lngdppc}. $\beta_{\mathrm{lnselect}}$ and $\beta_{\mathrm{lnsnuclear}}$ fluctuate more steadily, indicating that the coefficient for the share of renewables and nuclear energy may be time-invariant (constant). The behavior of β_{lngdppc}, which closely follows $\beta_{\mathrm{lnemissionspc}}$, is noteworthy. This suggests that GDP growth is a significant predictor of emissions growth.

For some country series, the sign orientations of $\beta_{\mathrm{lnemissionspc}}$ and β_{lngdppc} are not similar in the renewables and the nuclear energy equations. The first reason for the distinction between the two equations is that, since nuclear energy has lower number of observations, TVC estimations did not yield similar estimates for $\beta_{\mathrm{lnemissionspc}}$ and β_{lngdppc}. Another reason is that changing one of the predictor variables (from *lnselectpc* to *lnsnuclearpc*) alters the variance-covariance matrix, resulting in different parameter estimates for $\beta_{\mathrm{lnemissionspc}}$ and β_{lngdppc}. Additionally, the literature finds that the relationship between GDP and CO_2 emissions varies in response to the source of energy variable used in a VAR framework, consistent with our findings for renewable and nuclear energy (Kang et al., 2019). Chebyshev's polynomials in Bierens and Martins Test approximately fit an optimal order of Fourier terms, allowing for smooth fluctuations in each case, so we cannot expect the dates for changes in the sign orientation of the coefficients to be exact. Thus, we can only make approximate interpretations.

The countries in our list other than China, Brazil, and India are developed countries. According to the EKC hypothesis, we would expect a negative relationship between emissions and GDP growth for these countries. However, in the US, France , Canada, Russia, and the UK, $\beta_{\mathrm{lnemissionspc}}$ and β_{lngdppc} have the same sign for most of the series, signaling the positive relationship between emissions and GDP. Literature claims that in the countries where the emissions possess an income elasticity that is positive but lower than unity, we can infer that emissions growth is slower than GDP growth. This is called relative decoupling of emissions and economic growth (Mikayilov et al., 2018; IEA, 2024).

Figures 4.2.2 and 4.2.3 show that the slope of the emissions growth plot is lower than that of GDP growth, which is the sign of decoupling. The phenomenon can be related to the improvements in energy intensity, electrification in diverse sectors like mobility, agriculture and heating, and significant declines in coal consumption in industry (IEA, 2024). Economic growth is also slowing in the developed countries, because of aging demographics, flat educational attainment and income inequality (Gordon, 2017). The impact of this slowdown on lowering emissions may have been more significant than the impact of the high levels of GDP and economic development itself. Thus, for these countries, we may interpret the positive relationship between emissions and GDP as; lower economic growth results in lower emissions (Fend et al., 2015; Shapland, 2019).

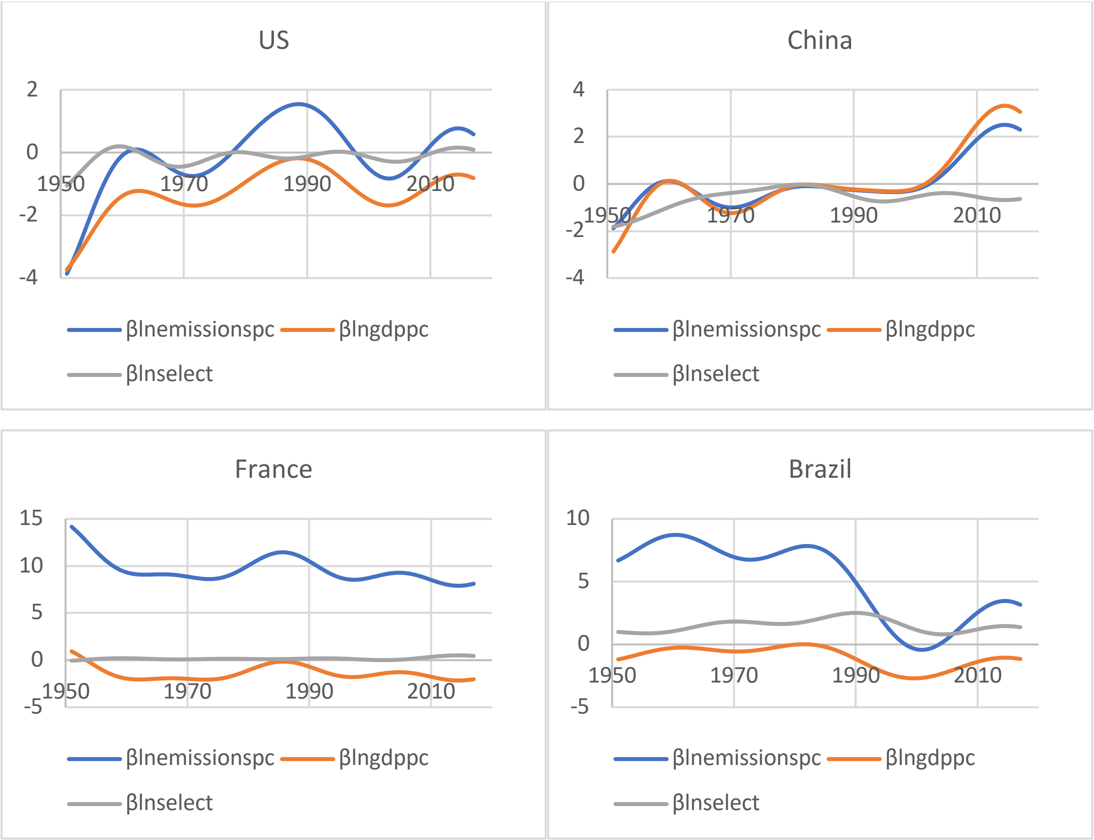

Figure 4.4.1 Time-Varying Cointegration Coefficients for Renewables

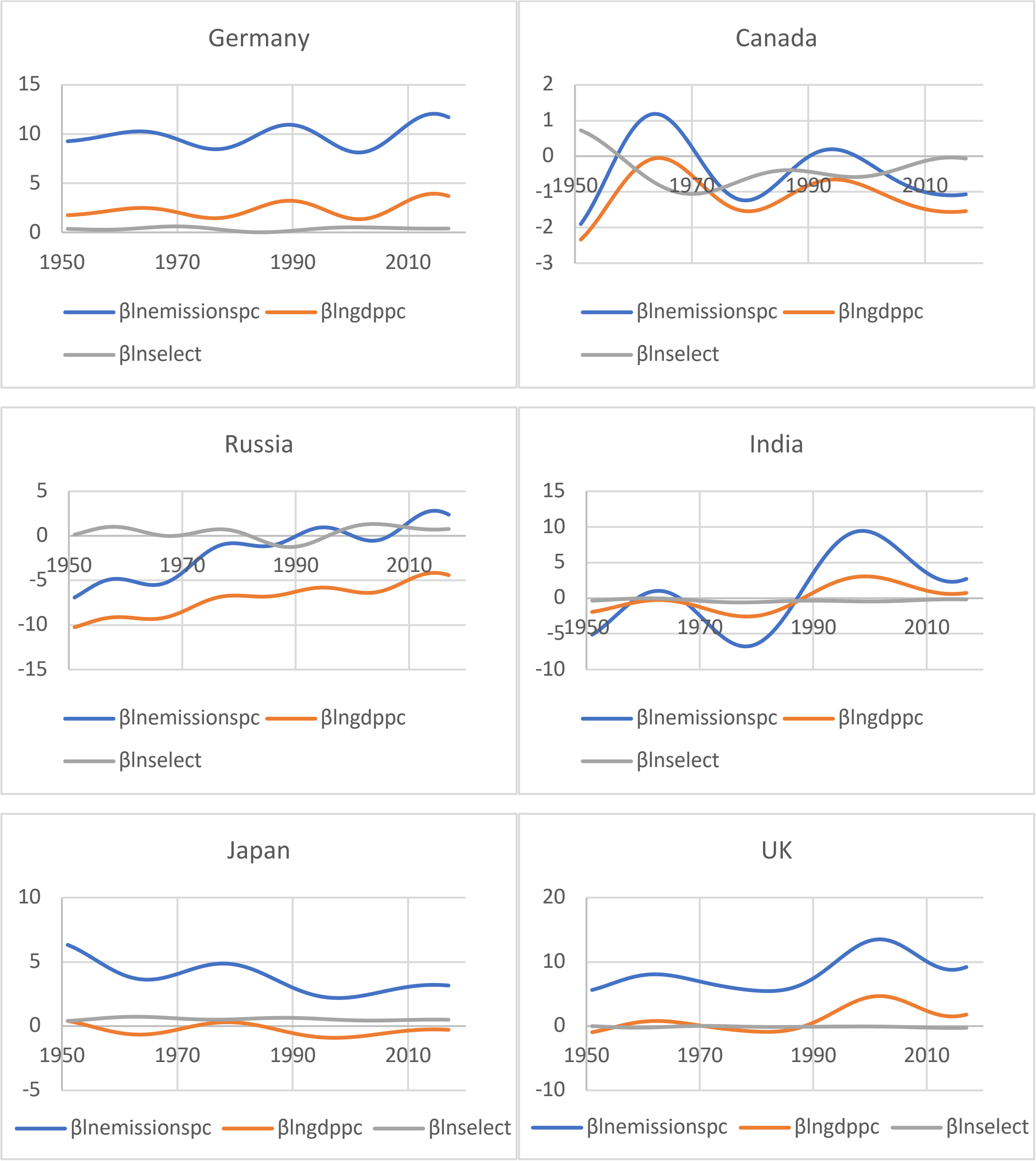

Figure 4.4.1 (continued)

In the UK, the relationship between emissions and GDP measures has turned from negative to positive especially after the 1990s. In France, the turning point is 2007 in Figure 4.4.2. Destek et al. (2020) finds that this relationship turns positive around 2008 Economic Crisis for most of the developed countries. The UK and France results may be in line with this finding only with an earlier turning point for the UK. Results for Germany is controversial. The emissions-GDP realtion is positive in Figure 4.4.1 and it is negative in the 2000s in Figure 4.4.2. Renewables equation of Germany is consistent with relative decoupling for Germany. Nuclear energy is stagnating around 2000s with Kyoto and decreasing around 2010s with the effects of Fukushima in Germany. The impact of these developments in nuclear energy may have partly resulted in increases in emissions from total energy consumption, reflecting as a negative relation between emissions and GDP in 2000s for the nuclear energy equation. In Brazil and Japan, the expected negative relationship is achieved. Higher economic growth may result in lower growth in CO_2 emissions for these two countries.

In Figure 4.4.1 we observe that $\beta_{\mathrm{lnselect}}$ is significantly different from zero only in China, Brazil, and Canada. Overall, we did not find evidence supporting the hypothesis that increasing shares of renewable energy will lead to decreases in CO_2 emissions. In Brazil and Canada, increases in the share of renewables growth are associated with increases in per capita emissions growth.

It appears that only in China, after the 2000s, increases in the growth of the share of renewables result in a decrease in emissions growth. This is a plausible result because China uniquely emphasizes transitioning to clean energy not only for environmental concerns but also for economic growth. The country views renewable energy as a sector to enhance international trade and broaden growth opportunities. In recent years, China has excelled in new sub-sectors related to clean energy, such as the rapid production of solar panels and renewable energy storage and distribution technologies. Studies claim that clean energy begins to reduce emissions after reaching a certain level of consumption (Chiu and Chang, 2009). Our results align with these claims, as China has shown the highest growth in renewable energy consumption, especially in recent years, reaching 401 million tons of oil equivalent (mtoe), almost twice that of the US.

Figure 4.4.2. shows that $\beta_{\mathrm{lnsnuclear}}$ is significantly different from zero for China, France, Germany, and Japan. These four countries have maintained a steady focus on nuclear energy for a long time. In France, growth in the share of nuclear energy results in lower growth in CO_2 emissions between 1960s and 2000s, while in Germany, per capita CO_2 emissions and share of nuclear energy have a negative relationship for the entire timeline. In France, nuclear energy was the primary clean energy resource until

Kyoto Protocol. Figure 4.2.1 shows the changes in the renewable and nuclear energy consumption. 2000s mark the turning point for the renewables sector in France with the promotion of renewable energy by the Kyoto Protocol. The downturn in nuclear energy is evident in the plots of the two resources.

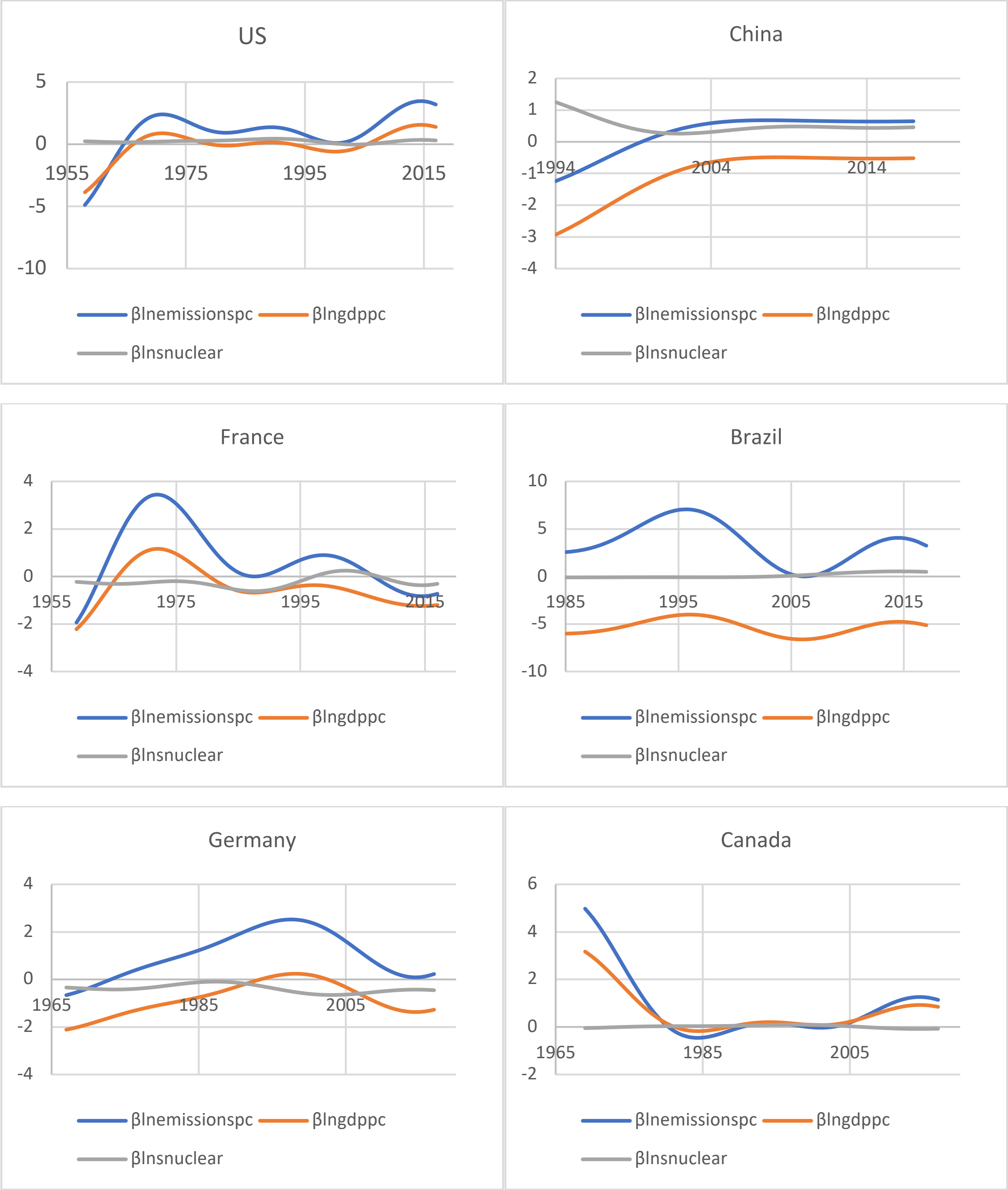

Figure 4.4.2 Time-Varying Cointegration Coefficients for Nuclear Energy

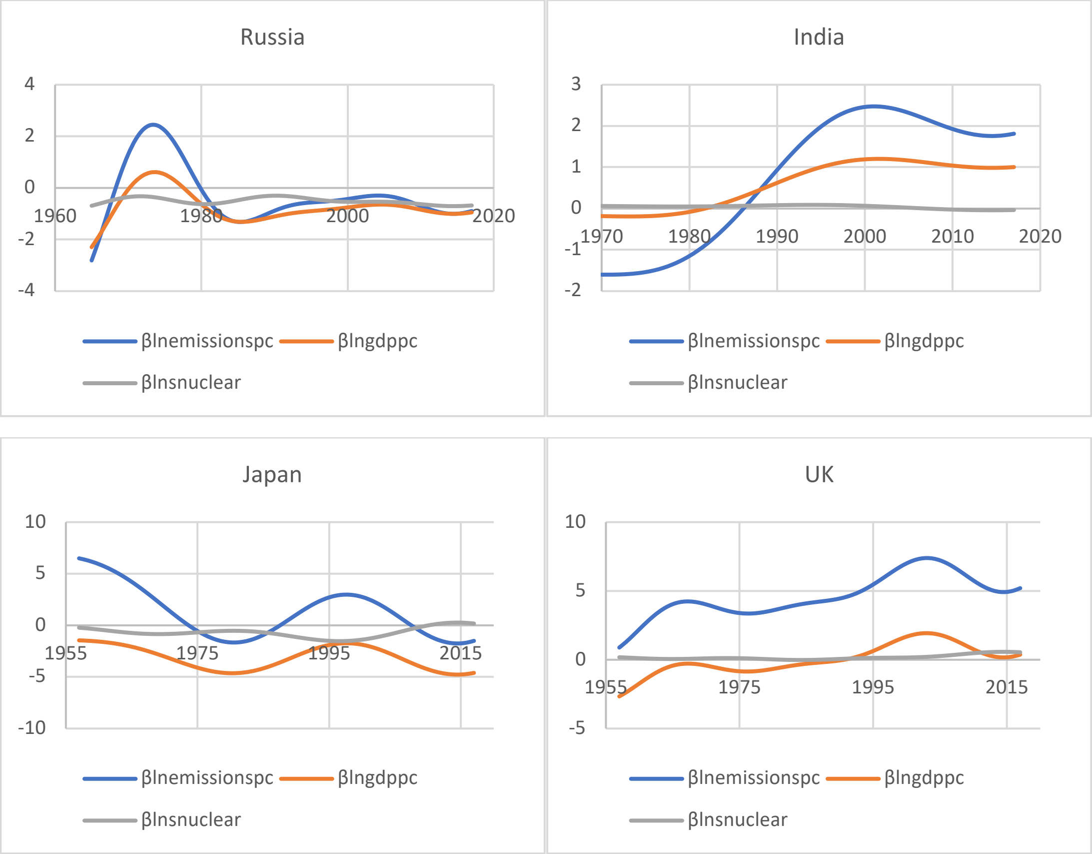

Figure 4.4.2 (continued)

The relationship between emissions and nuclear energy has changed with these developments, lowering the impact of nuclear energy on emissions. In China, nuclear energy and emissions growth move in the same direction but the coefficients for both variables are very low. Thus, we cannot infer that nuclear energy has a significant long-run impact on emissions in China. In Japan, this relationship changes over the analyzed period. For instance, from the 1990s to the 2010s, growth in the share of nuclear energy decreases CO_2 emissions growth. However, the coefficient for the share of nuclear energy becomes very low towards the end of the analyzed period, which includes the dates around and after the Fukushima Disaster in 2011.

4.5. Conclusion

This study contributes to the emissions literature by examining renewable energy and nuclear energy as separate clean energy components using a time-varying cointegration analysis, which accounts for smooth regime changes. Although existing studies have analyzed these components with time-invariant cointegration methods, we emphasize the importance of time-varying analysis and proceed with this approach. Additionally, unlike previous research, we use the shares of clean energy consumption as a more accurate measure to capture the impact of clean energy from an environmental perspective.

For this purpose, we analyze data from the period 1950-2020, focusing on ten countries with the highest levels of clean energy consumption, including both developed and developing nations. This specific timeline allows us to account for the impact of three significant events in the history of clean energy: the oil crisis of the 1970s, the Kyoto Protocol in the 2000s, and the Fukushima Nuclear Disaster in 2011. Using Bierens and Martins' Time-Varying Cointegration Test (2010) and Chebyshev's time polynomials, our analysis is able to capture the effects of these events within the cointegration relationship.

For the countries where a cointegration (CI) relationship with time-invariant parameters was not detected - specifically the US, Brazil, Russia, and India - the application of time-varying cointegration (TVC) using Chebyshev's polynomials successfully identifies CI. When allowing for time-varying parameters, all countries demonstrate long-run relationships between emissions, the share of clean energy, and GDP series.

The data analysis presented in Figures 4.2.2 and 4.2.3 reveals a gradual divergence in the growth rates of per capita emissions and per capita GDP for the US, France, Germany, and the UK. In these countries, the growth of per capita emissions is decelerating compared to the growth of per capita GDP. The time-varying long-run parameters of per capita emissions and per capita GDP for these countries generally exhibit the same sign. These results are in line with the TVC Test parameters in terms of “relative decoupling”.

Examining the sign and magnitude of the CI parameters, we find no clear linkage between decreasing emissions and higher GDP and clean energy shares. Thus, if countries do not change their current clean energy consumption paths, only factors such as declining economic growth rates, technological advancements in energy efficiency, and cleaner fossil fuel processes, as discussed in COP28, may contribute to lowering emissions growth. In the nuclear energy equations for Germany, France, and Japan, we observe a negative impact of the share of nuclear energy on emissions, the impact becoming lower for France in the 2000s and for Japan in the 2010s. Considering the current trajectories of the countries in this study, the share of renewable energy also does not appear to have a significant long-term impact on reducing emissions. The emissions-reducing effect of higher renewable energy shares is evident only in China, which has a substantially higher and fast-growing renewable energy consumption compared to the other countries analyzed.

In conclusion, despite the cleaner energy mix, most countries remain dependent on fossil fuels. The consumption of harmful energy sources continues to rise, leading to increased CO_2 emissions. In the context of growing total energy consumption, fossil fuels are not being replaced by renewables; instead, renewables are used to consume more energy without reducing the reliance on harmful energy sources. The literature indicates that following the 2008 economic crisis, many countries shifted their focus from environmental concerns to economic priorities. This shift may explain why CO_2 emissions have not decreased despite increased clean energy consumption. However, change is always possible. China's example, with its significant focus on the clean energy sector, suggests that other countries might also increase their emphasis on clean energy, particularly renewables. Incorporating renewable energy across various sectors, including industrial applications, transportation, and residential activities, could lead to reduced CO_2 emissions. Additionally, countries should address other high-emission factors such as waste management, deforestation, and agriculture.

Future studies should consider that the cointegration (CI) relationship may have undergone both sharp and smooth changes. A more robust exploration of cointegration is necessary, along with the development of new Cointegration Tests that accommodate multiple breaks. These tests should be capable of pinpointing exact break dates and structures. Also, quantile cointegration studies accounting for the asymmetric responses of the long-term relations to the developments in the climate management and energy sector may provide valuable insights to the field. Future studies should also focus on the impact of energy efficiency indicators, along with clean energy shares, on the emissions. A positive relationship between clean energy shares and emissions may mean that a country is ignoring the energy efficiency requirements, but we need further assessments for sound implications.

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A. CHAPTER 3 APPENDICES

SAMPLE QUANTILE REGRESSION REPRESENTATION

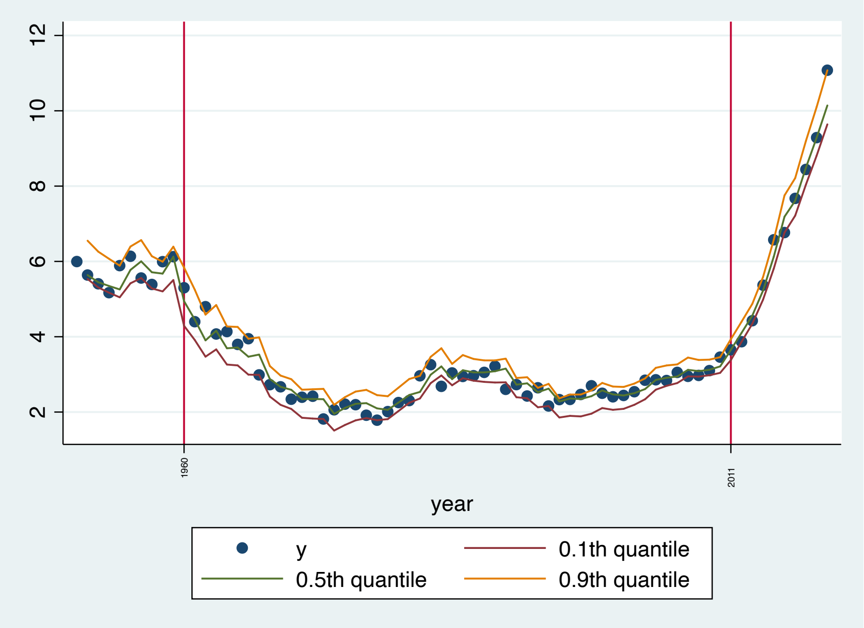

Figure A.1 Quantile Regression Model for Japanese Share of Renewables (%)

ALTERNATIVE TO 2 STEP PROCEDURE

A more consistent approach may be choosing the break points and Fourier frequencies in a more comprehensive SSR equation. Obtain k, β and δ, minimizing:

$$\sum_{k=1}^{5}\sum_{i=1}^{m+1}\sum_{t=T_i-1}^{T_i}[y_t - x_t'\beta - z_t'\delta]^2 \quad \text{(A.1)}$$

However, optimization with this SSR needs a more complicated algorithm with additional terms. The estimation could be time consuming. Thus, we left this method for future studies.

HANSEN'S CRITICAL VALUES

Table A.1 Hansen (1995) Critical Values

δ^2	**Standard**			**Demeaned**			**Detrended**		
	1%	5%	10%	1%	5%	10%	1%	5%	10%
1	-2.57	-1.94	-1.62	-3.43	-2.86	-2.57	-3.96	-3.41	-3.13
0.9	-2.57	-1.94	-1.61	-3.39	-2.81	-2.5	-3.88	-3.33	-3.04
0.8	-2.57	-1.94	-1.6	-3.36	-2.75	-2.46	-3.83	-3.27	-2.97
0.7	-2.55	-1.93	-1.59	-3.3	-2.72	-2.41	-3.76	-3.18	-2.87
0.6	-2.55	-1.9	-1.56	-3.24	-2.64	-2.32	-3.68	-3.1	-2.78
0.5	-2.55	-1.89	-1.54	-3.19	-2.58	-2.25	-3.6	-2.99	-2.67
0.4	-2.55	-1.89	-1.53	-3.14	-2.51	-2.17	-3.49	-2.87	-2.53
0.3	-2.52	-1.85	-1.51	-3.06	-2.4	-2.06	-3.37	-2.73	-2.38
0.2	-2.49	-1.82	-1.46	-2.91	-2.28	-1.92	-3.19	-2.55	-2.2
0.1	-2.46	-1.78	-1.42	-2.78	-2.12	-1.75	-2.97	-2.31	-1.95

(Hansen, 1995, p. 1155)

Equations for point estimation of critical values for detrended series are calculated as follows:

$\mathrm{CV}_{1\%} = 0.905(\delta^2)^2 - 2.243(\delta^2) - 1.767$

$\mathrm{CV}_{5\%} = 0.921(\delta^2)^2 - 2.170(\delta^2) - 2.135$

$\mathrm{CV}_{10\%} = 0.890(\delta^2)^2 - 2.005(\delta^2) - 2.813$

B. CHAPTER 4 APPENDICES

COINTEGRATION TESTS WITH SHARP STRUCTURAL BREAKS

Gregory and Hansen (1996) methodology looks for cointegration in the presence of breaks under the long-run equation:

$$y_{1t} = \alpha_1 \boldsymbol{y}_{2t} + \alpha_1 \boldsymbol{y}_{2t} DU_{T_b} + v_1 + v_2 DU_{T_b} + \delta_1 t + \delta_2 DU_{T_b} + e_t \qquad \text{(A.1)}$$

$$DU_{T_b} = \begin{cases} 0, & t \leq T_b \\ 1, & t > T_b \end{cases}$$

where; y_{1t} is a single dependent variable while $\boldsymbol{y}_{2t}$ is a vector of variables that can be represented by a cointegrating relation with y_{1t}. It also integrates lagged variables in the regression equation (6). The methodology allows for only one sharp break in the level, trend and/or regime. Regression residuals are estimated for all possible break types and dates, and then the stationarity of the residuals is tested by DF, estimating the nonstandard critical values for the test statistics by simulation. The break date chosen is the date that gives the residuals with the smallest test statistic.

Hatemi-J (2008) expands Gregory and Hansen (1996) methodology to allow for two breaks, while Maki (2012) introduces a test allowing for multiple unknown breaks based on Gregory and Hansen's test. Maki Test looks for the number and position of breaks in a simultaneous manner. If only one break is allowed, the procedure is the same as Gregory and Hansen (1996), choosing the break date that gives the minimum t-statistic for unit root testing. If more than one break is allowed, the procedure estimates the first break date by minimizing the SSR of equation (6), similar to Bai and Perron (2003) methodology, then feeding the first break date parameters into the equation as a non-shifting regressor, $DU_{T_{b1}}$. The methodology estimates the second break among remaining possible break dates as the date that gives the minimum t-statistic for the resulting equation with the shifting regressor $DU_{T_{b2}}$:

$$y_{1t} = \alpha_1 \boldsymbol{y}_{2t} + \alpha_1 \boldsymbol{y}_{2t} DU_{T_{b1}} + \alpha_1 \boldsymbol{y}_{2t} DU_{T_{b2}} + v_1 + v_2 DU_{T_{b1}} + v_2 DU_{T_{b2}} + \delta_1 t + \delta_2 DU_{T_{b1}} + \delta_2 DU_{T_{b2}} + e_t \quad \text{(A.2)}$$

The search for possible breaks continues in this manner until reaching the maximum number of breaks allowed. The breaks augmented equation with the minimum t-statistic for the resulting residuals is chosen to determine the optimum number and dates of breaks.

There are also panel cointegration studies with structural breaks. Westerlund (2006) utilizes a method involving the minimum SSR approach by Bai and Perron (2003) to estimate structural breaks on the constant term of the panel version of the above long-run regression equations:

$$y_{1jt} = \alpha_1 \boldsymbol{y}_{2jt} + v_1 + v_2 DU_{jT_b} + \delta_1 t + e_{jt} \quad \text{(A.3)}$$

where j stands for the panel individuals. He uses sieve-bootstrap innovations from panel VECM to approximate the cross-section dependence and time series dependence of the disturbances.

FITTED VALUES FOR THE TIME-VARYING COINTEGRATION

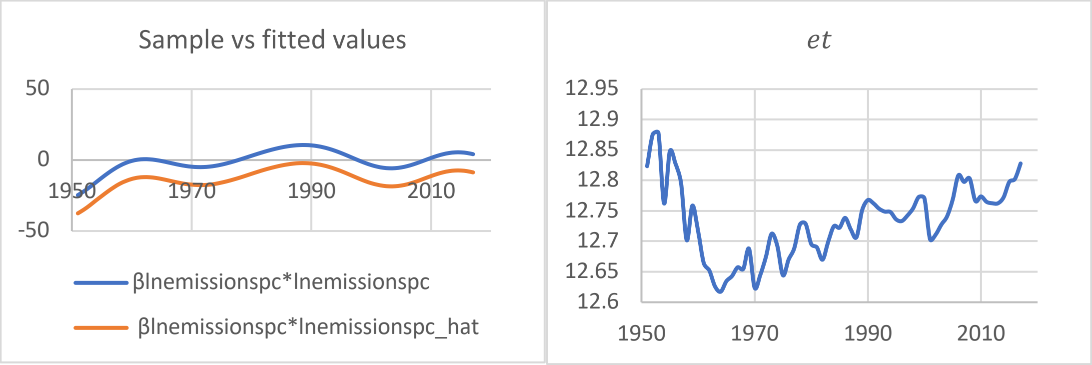

Figure B.1 Time-Varying Cointegration estimations for the renewables equation of The US

Here, $\beta_{\text{lnemissionspc}}$ is also an estimate. We only provide this graph as an intuitive comparison to time invariant parameters case. It is evident that e_t has a constant element because we use a VECM model with drift term.

C. CURRICULUM VITAE

Saliha Ergün Tanrıverdi

EDUCATION

Middle East Technical University – PhD in Economics	09/2016-09/2024
Bilkent University – MA in Economics	09/2012-06/2014
Georgia Institute of Technology – MS in Economics	08/2010-12/2011
Kansas State University – Exchange Program, Chemical Engineering	08/2008-12/2008
Boğaziçi University – BS in Chemical Engineering	09/2005-01/2010

RESEARCH

Fields of Interest: Econometrics, Applied Econometrics, Energy Economics, Environmental Economics, Development Economics

Middle East Technical University – PhD Thesis 09/2019-09/2024

Advancements in Energy Economics- Historical Perspectives, Modeling Persistence, and Time-Varying Cointegration

- Climate Change and Energy Transition: A Historical Review
- Modeling Persistence Characteristics of Primary Energy Consumption from Clean Resources, Considering Asymmetries and Structural Breaks.
- Time-Varying Cointegrating Relation Between CO_2 Emissions and Clean Energy Consumption

Conferences Attended

ICE-TEA 2022: 09/2022

Modeling persistence characteristics of primary energy consumption from clean resources: considering asymmetries and structural breaks

MIC 2022: 06/2022

Does Share of Renewables and Share of Clean Energy in Primary Energy Consumption Show Long Memory Under Sharp and Smooth Structural Changes?

Bilkent University – MA Thesis 09/2013-06/2014

Impact of Technology Development Areas on Innovation in Turkey

Georgia Institute of Technology - MS Thesis 06/2011-01/2012

UNICEF and Ministry of Education’s Joint Girls’ Education Program in Turkey, “Haydi Kızlar Okula!”: Did it work? What is the aftermath?

BS Thesis: 08/2009-12/2009

Why HDI (Human Development Index) beats GII (Global Innovation Index) in explaining energy consumptions and CO_2 emissions?

WORK EXPERIENCE

BETAM, Bahçeşehir University Center for Economic and Social Research. 08/2023-present

Researcher**:** Research on Development in Turkey's Employment and Growth Statistics.

Boğaziçi University 09/2019-09/2021

Teaching Assistant: Courses taught:
- Principles of Microeconomics
- Mathematical Statistics II
- Econometrics
- Advanced Econometrics
- World Economic History
- Growth and Development
- Special Topics in Banking and Finance

Bilkent University 09/2012-07/2014

Teaching Assistant: Courses taught:
- Introduction to Economics
- International Economics I-II

Institute of Strategic Thinking (SDE) 02/2012-07/2012

Research Assistant**:** Research on global economics topics. Organizing conferences, seminars, and media events. In charge of the group preparing country profiles according to the year plan. Monthly articles in the magazine "Stratejik Düşünce" and on the web (www.sde.org.tr).

Georgia Institute of Technology, Health Systems Institute 08/2011-12/2011

Research Assistant**:**

Healthcare in Turkey Project:
Turkey's Healthcare system; past and current status, changes and future expectations.
- Determining the high-risk areas. Constructing possible research frameworks.
- Building international collaboration with Turkish universities and organizations.
- Searching for informational and financial support.

Joint Research Achievements:
- Georgia Inst of Technology & Koç University
- Georgia Inst of Technology & TOBB University

Research Topics:
- Impact of preventive care on health expenditures: Is it possible to sustain the costs with more focus on preventive care during the Healthcare Transformation period in Turkey?
- Determining the requirements for a more efficient primary care: Study on family physicians and nurses in Turkey
- Testing whether treatment choices and values assigned to treating patients are different for private hospitals from public hospitals in Turkey

B'iota Laboratories, Pharmaceuticals and Cosmetics 07/2009-05/2010

R&D Project Manager: In charge of production steps from the design until the end product phase. Background research. Lab-scale production and design experiments. Raw material selection and provision. Initial large-scale production. Performance testing. Benchmark assessment. Product development. Licensing and Patenting.

SKILLS

- Microsoft Office, C, MATLAB, SAS, Stata, Arena, R, Gauss, Eviews
- Turkish (native), English (fluent), French (basic), Arabic (basic)

D. TURKISH SUMMARY / TÜRKÇE ÖZET

Bölüm 1: Giriş

Onlarca yıldır artan çevre ve iklim kaygıları, endüstrileri daha temiz ve daha sürdürülebilir enerji kaynaklarını kullanmaya yöneltmiştir. “Enerji Dönüşümü” olarak bilinen bu yolculuktaki gelişmeler daha uygun maliyetli ve kullanışlı enerji üretim yöntemlerinin geliştirilmesine yol açmıştır. Enerji dönüşümünün aslında yeni bir kavram olmadığını belirtmek isteriz. Tarihsel olarak odundan kömüre geçişin ilk gerçekleştiği 13. yüzyıla kadar uzanmaktadır. Ancak 19. yüzyıla kadar kömür birincil enerji kaynağı haline gelmemiştir. İkinci büyük geçiş, 1859'da petrolün keşfiyle gerçekleşmiştir ve bu keşif kömürden petrole geçişe işaret etmektedir. Ancak petrolün birincil küresel enerji kaynağı haline gelmesi 1960'lı yıllara kadar mümkün olmamıştır (Yergin, 2020).

Enerji geçişinin mevcut aşaması, fosil yakıtlardan temiz enerji kaynaklarına doğru büyük bir değişimin hayata geçişi olarak görülebilir. Temiz enerji dediğimizde birincil olarak nükleer ve yenilenebilir kaynaklardan elde edilen enerjiyi ele almaktayız. Nükleer enerji, istikrarlı ve yüksek düzeyde enerji tedariki avantajı sunarak, ekonomik açıdan çekici bir kaynak olarak görülmektedir. Bununla birlikte, nükleer enerji konusunda doğal risklere ilişkin endişeler, yenilenebilir enerji kaynaklarını insan güvenliği ve çevresel sürdürülebilirlik açısından daha cazip bir seçim haline getirmiştir.

Şu anda yenilenebilir enerji kaynakları, küresel birincil enerji tüketiminin yaklaşık %14'ünü oluşturmaktadır. Bu oran, 1950'lerde %5 civarındayken bu hızlı artış ciddi bir değişime işaret etmektedir. Nükleer enerji ise birincil enerji tüketiminin %4'üne tekabül etmektedir. Bu rakam, 1950 ile 2000 yılları arasında %0'dan %7'ye yükselmiş ve daha sonra mevcut seviyesine düşmüştür (BP Dünya Enerji İstatistik İncelemesi, 2022). Yenilenebilir enerji açısından, güneş fotovoltaik (PV) ve rüzgar teknolojileri, geleneksel yenilenebilir kaynakların etkin bir şekilde yerini almıştır. Bu teknolojiler, biokütle, odun ve hidroelektrik kaynaklarına göre daha çevre dostu ve endüstriye uyumlu görüldükleri için sıklıkla 'modern yenilenebilir kaynaklar' olarak anılmaktadır (Yergin, 2020).

Enerji geçişi kademeli ve karmaşık olmasına rağmen inkar edilemez bir şekilde devam etmektedir. Günümüzün ve yakın geleceğin teknolojisi ve yenilenebilir kaynakların güvenilmezliği nedeniyle küresel elektrik üretiminin tamamen yenilenebilir olamayacağı öngörülmektedir. Şu ana kadar temiz enerji sektörünün büyümesi, enerji egemenliği ve iklim değişikliğine ilişkin endişeleri telafi edememiştir. Konu, özellikle Rusya'nın Şubat 2022'de Ukrayna'yı işgal etmesiyle de vurgulanan siyasi ve ekonomik popülerliğini korumaktadır. Ayrıca, iklim değişikliğini hafifletmeyi amaçlayan net-sıfır karbon emisyonuna yönelik küresel bir baskı da mevcuttur. Bugün emisyonların %76'sını oluşturan Çin, ABD ve AB gibi önde gelen sanayi ülkeleri, iklim değişikliği konusunda sıkı önlemler alma sözü vermiştir (UNEP, 2022).

Enerji geçişinin son aşaması, kısmen enerji egemenliğine ilişkin kaygılar ve uluslararası enerji şoklarının etkilerini hafifletme zorunluluğu nedeniyle ortaya çıkmıştır. Nükleer enerjinin teşviki, 1957'deki Süveyş Krizi ve 1970'lerdeki petrol krizinin ardından önem kazanmıştır. Yenilenebilir enerji kaynaklarının kökleri antik su değirmenlerine ve yel değirmenlerine dayansa da yenilenebilir enerji sektörünün hızlı büyümesi, petrol şirketlerinin petrol arzındaki belirsizliklere karşı önlem almalarına bağlanabilir. 1987-Tek Avrupa Yasası gibi daha sonra düzenlenen politikalar da Avrupa enerji pazarını çeşitlendirerek bu geçişin ilerletilmesinde önemli bir rol oynamıştır. Ayrıca, endüstri ölçeğinde güneş ve rüzgar teknolojilerinin 19. yüzyılın sonlarına kadar ortaya çıkmadığını da belirtmek gerekmektedir.

Son zamanlarda çevresel kaygılar giderek daha fazla önem kazanmaya başlamış ve yavaş yavaş enerji egemenliği konusunun önüne geçmiştir. İklim değişikliğine karşı mücadele, sera gazı emisyonlarının azaltılmasına yönelik ülkeye özgü sınırlar belirleyen Kyoto Protokolü (1997-2005) ile 2000'li yıllarda başladı. Paris Anlaşması (2015), Birleşmiş Milletler üyelerini 21. yüzyılda küresel sıcaklık artışlarını 2 santigrat derece ile sınırlandırmaya yönelik çalışmaya yönelterek küresel çabaları daha da güçlendirdi. Bu uluslararası anlaşmalar, artan toplumsal farkındalıkla birlikte, enerji tüketiminin azaltılmasını ve yenilenebilir enerji kaynaklarına geçişi önemli ölçüde desteklemiştir. Fosil yakıtların çevresel etkilerine ilişkin endişeler arttıkça, temiz enerji alternatifleri ve enerji kaynaklarının bileşimi ile ilgili zararlı yan ürünlerin seviyelerine verilen önem de artmaktadır.

Geçiş süreci boyunca temiz enerji sektörü önemli değişikliklere uğramıştır. Bu tezin ikinci bölümünde temiz enerji sektörünün önde gelen on ülkesinde (Çin, ABD, Fransa, Brezilya, Almanya, Kanada, Rusya, Hindistan, Japonya ve Birleşik Krallık) temiz enerji tüketiminin tarihsel gelişimi araştırılmaktadır. 1950'den 2020'ye kadar olan dönemi kapsayan çalışma, önemli olayları ve bunların sektör üzerindeki etkilerini araştırmaktadır. Bu bölümde başlıca uluslararası çevre anlaşmalarının şartları ve perspektifleri ele alınmaktadır. Bunlar gelişmiş ve gelişmekte olan ülkelerin enerji tüketimi tercihlerini şekillendiren Montreal Protokolü, Kyoto Protokolü ve Paris Anlaşması’dır. Bu anlaşmaların gönüllülük esasına dayalı olması, etkinlikleri konusunda şüpheler uyandırmaktadır. Bu çalışma uluslararası toplumun, Nordhaus'un (2020) da önerdiği gibi, her ülkenin katılmak istediği ve kimsenin ayrılmak istemediği, katılmayan ülkelerin ise cezaya tabi tutulacağı, kulüp benzeri bir yapıya sahip, daha işlevsel bir anlaşma tasarlamak için çalışmalar yapmalarını önermektedir. Bu oluşturulacak yeni anlaşmaların ceza ve şartları ise her ülkeye göre uyarlanabilir.

Üçüncü bölümde temiz enerji serilerine gelen şokların asimetrik özelliklerine göre kalıcı mı yoksa geçici mi etki yarattığını tespit etmeyi amaçlıyoruz. Seri kalıcılık (uzun hafıza) gösterdiğinde, geçici şoklar istatistiksel momentler (ortalama ve varyans gibi) üzerinde uzun vadeli etkiler yaratır. Enerji değişkenlerinin uzun hafıza özellikleri politika ve işletme kararlarının önemli belirleyicileridir. Uzun hafıza dinamiklerini daha iyi anlamak için seriyi yapısal kırılmaların doğasını da incelikle dikkate alarak modellemek önemlidir. Üçüncü bölüm, Koenker ve Xiao'nun (2004) Kantil Birim Kök Testi'nin bireysel kantillerde hem keskin hem de yumuşak yapısal kırılmaların etkilerini hesaplayacak şekilde değiştirilmiş bir versiyonuyla literatüre katkıda bulunmaktadır. Mevcut çalışmalardan farklı olarak yenilenebilir ve nükleer enerji pay serilerinin kalıcılık davranışlarını ülke bazında ayrı ayrı ve karşılaştırmalı olarak inceliyoruz. Bu bölümde, temiz enerji tüketimi en yüksek olan ve güvenlik endişeleri nedeniyle nükleer enerji tüketimini azaltan ya da nükleer enerjiye en başından beri temkinli yaklaşan ülkelerden elde edilen veriler kullanılmaktadır. Bu ülkeler Fransa, Brezilya, Almanya, Japonya ve Birleşik Krallık'tır. Sektörün önde gelen ülkelerinin farklı kalıcılık özelliklerinin daha iyi kapsanabilmesi için Çin ve ABD de incelemeye alınmıştır. Ampirik sonuçlar, nükleer enerjide genel bir gerileme olduğunu, hızlı teknolojik gelişme ve düşük fiyatlar nedeniyle yenilenebilir enerjinin yükselişte olduğunu göstermektedir. Bu bulgular, temiz enerjinin uzun hafıza özelliklerinin ülkeye ve kaynağa özgü yöntemlerle incelenmesi yönündeki önerimizi vurgulamaktadır. Bu çalışma özelinde, temiz enerjinin uzun hafıza analizinde zaman serisi olarak temiz enerji bileşenlerinin birincil enerji kaynakları içindeki paylarının kullanılması, temiz enerji tüketiminin çevreye duyarlı bir bakış açısıyla analiz edilmesi açısından aydınlatıcıdır. Çünkü iklim değişikliğinin yavaşlatılması, enerji kullanımında fosil yakıtlardan temiz kaynaklara geçiş yapılmasını gerektirmektedir. Temiz enerji tüketim düzeyleri bu gerekliliği incelemek konusunda yetersiz kalmakta, temiz enerji payları ise sorunu daha doğru bir şekilde incelemeye olanak sağlamaktadır.

Dördüncü bölüm, ikinci ve üçüncü bölümlerin aydınlatmaya çalıştığı fikirlere bütüncül bir bakış getirmektedir. Önceki bölümlerde çevresel bozulma ve temiz enerji bileşenlerinin gelişim yolundaki olayların bu serilerin istatistiksel özelliklerini önemli ölçüde etkilediği sonucuna varılmıştır. Bu bölümde ise iklim değişikliği ile temiz enerji tüketiminin uzun vadeli ilişkileri (eşbütünsellikleri) olup olmadığını sorgulamaktayız. Bu soruyu yanıtlamak için, Bierens ve Martins'in (2010) Zamanla Değişen Eşbütünsellik Testi kullanılarak kişi başına CO2 emisyonları ile yenilenebilir ve nükleer enerji kaynaklarının payları arasındaki zamanla değişen eşbütünleşme ilişkisi araştırılmaktadır. Aynı zamanda kişi başına düşen GSYİH de bu ilişkide bir değişken olarak kullanılarak ülkelerin ekonomik kalkınma düzeylerinin etkisi de göz önünde bulundurulmaktadır. Bu tarihe kadar bu ilişki, temiz enerji sektöründe önde gelen her ülke için yenilenebilir ve nükleer enerjinin farklı değişim süreçleri dikkate alınarak zamanla değişen eşbütünleşme metodolojileri ile dikkatli bir şekilde incelenmemiştir. Sonuçlarımız, zaman değişimi göz önüne alındığında, CO2 emisyonlarının tüm ülkelerde her iki temiz enerji bileşeninin paylarıyla eşbütünleşik olduğunu göstermektedir. Yalnızca Çin'de yenilenebilir enerji payındaki artışın emisyon artışıyla önemli bir negatif ilişki içinde olduğuna dair kanıt bulunmuştur. Çin, yalnızca 15 yıl içinde ABD'nin yenilenebilir enerji tüketim seviyelerinin iki katı tüketimiyle yenilenebilir enerji tüketiminde lider ülke haline gelmiştir. Bu nedenle, artan yenilenebilir enerji tüketimiyle desteklendiğinde iklim değişikliğiyle mücadelenin hem çevreye hem de ekonomik büyümeye fayda sağlamasının imkansız olmadığını iddia etmekteyiz.

Bölüm 2: İklim Değişikliği ve Enerji Dönüşümü: Tarihsel Bir İnceleme

İkinci bölümde uygulanan analizler ve gözlemler gösteriyor ki 1992'den bu yana UNFCCC'yi takip eden çabalar emisyonlarda bir miktar azalmaya yol açsa da gerekli "dramatik kesintiler" gerçekleştirilmemiştir. Kyoto Protokolü ve Paris Anlaşması etrafındaki belirsizlik devam etmektedir. Kyoto Protokolü, her ülkenin sınırlı bir emisyon hesabına sahip olduğu ve bu sınırlar dahilinde emisyon ticareti yapabileceği karbon emisyonları için bir piyasa yapısı oluşturmaya çalışmıştır. Bununla birlikte, protokolün gönüllü yapısı, sorgusuz geri çekilme ve hazıra konma gibi durumlara izin verilmekteydi. Kyoto Protokolü'nün başarısızlığının yerini, evrensel 1,5°C hedefi ve NDC'ler (Ulusal Katkı Beyanı) ile hem yukarıdan aşağıya hem de aşağıdan yukarıya bir yaklaşım benimseyen bir stratejiye sahip Paris Anlaşması aldı. ABD'nin Kyoto Protokol'ünden sonra Paris Anlaşması'ndan da geri çekilmesi bu yaklaşımın tutarlılığını baltaladı ve ikili stratejiyi uygulanamaz hale getirdi. Yine Anlaşmanın Kyoto Protokol'ü gibi koordinasyonsuz ve gönüllü doğası başarısızlıkla sonuçlanmıştır (Nordhaus, 2020). UNFCCC tarafından başlatılan uluslararası çabalardaki son gelişme, Kasım 2023'te düzenlenen COP28'dir. Pek çok temsilci tarafından potansiyel bir atılım olarak tanımlanan zirveye yönelik yüksek beklentilere rağmen sonuçlar bu beklentileri karşılamamıştır.

İklim ve enerji düzenlemelerinin ele alınması, devlet düzeyinde veya kar amacı gütmeyen uluslararası kurumlar tarafından müdahaleleri gerektirmektedir; çünkü serbest piyasa ve siyasi kurumlar, iklimin korunması ekonomik büyüme süreçlerinin ayrılmaz bir parçası olmadığı sürece bu konuya tek başına öncelik vermeyecektir. Bir iklim politikası aracı olarak emisyon izinleri, iklim kaygılarını hem firma düzeyinde hem de hükümet düzeyinde optimizasyon problemlerine entegre etmektedir. Ancak küresel sıcaklık artışlarını 1,5°C'nin altında tutmak için izin verilen emisyon düzeyini belirlemek zorlayıcıdır. Çok fazla izin verilmesi emisyon hedeflerine zarar verirken, çok az sayıda izin verilmesi endüstriyel üretimi ve arzı kısıtlar. Bu ikilem, karbon vergileri ve temiz enerji sübvansiyonları gibi diğer düzenlemeler için de geçerli olup bilimsel bir odaklanmayı gerektirmektedir.

Hükümetler de iklim değişikliğinin uzun vadeli etkilerini ele almak için en uygun enerji kullanımını ve iklim politikalarını belirlemelidir. Bununla birlikte, liderler uzun vadeli iklim meselelerinin çözülmesine yönelik adımlar yerine kısa vadeli seçim çizelgelerine öncelik verdiğinden, siyasi döngüler genellikle bireysel hükümetleri kısıtlamaktadır. Sonuç olarak, üretimi ve ekonomik büyümeyi yavaşlatabilecek iklim politikaları genellikle seçim dönemlerinde pek rağbet görmemektedir. Bu nedenle, iklim değişikliğiyle mücadele, hükümet değişikliklerinden bağımsız, bireysel bir kurum altında devlet düzeyinde özel bir odaklanmayı gerektirir.

Emisyon hedeflerindeki eksiklikleri ölçmenin bir zorluk olmasıyla beraber iklim değişikliğini ön plana alacak bir siyasi irade sağlamak başka bir zorluktur. 2015'teki Paris Anlaşması'ndan bu yana, iklim değişikliğini engellemek konusunda artan uğraşılar ve daha etkili NDC'lerle bir ilerleme kaydedilmiştir. Buna rağmen iklim değişikliğinin azaltılmasına yönelik yatırımların önemli ölçüde artması gerekmektedir. Küresel enerji yatırımlarının 2030 yılına kadar altı kat artması gerekmektedir (Black vd., 2023). Temiz enerji konvansiyonel enerjiye göre daha çok tercih edilebilmesi için daha ucuz olmalıdır. Güneş panelleri, rüzgar türbinleri, temiz enerji depolama teknolojileri ve elektrikli araçların maliyetlerinin teknolojik gelişmeler sayesinde düşmesi gerekmektedir. Şekil 2.3.18, yenilenebilir enerji maliyetlerindeki düşüşün devam ettiğini, fotovoltaik güneş ve kara rüzgar teknolojileri için Seviyelendirilmiş Enerji Maliyetinin 2010'dan bu yana tarihi en düşük seviyelere ulaştığını ve bu teknolojilerin 2015'ten bu yana en ucuz enerji kaynakları haline geldiğini göstermektedir. Ancak depolama maliyetleriyle ilgili endişeler devam etmektedir (Lazard, 2023).

İklim değişikliğine karşı önlem almamanın maliyetinin iklim değişikliğini önleyici yatırımların maliyetini aşması beklenmektedir. Araştırmalar, iklim değişikliğini hafifletmedeki başarısızlığın GSYH'yi gelişmiş ülkelerde %1-2, gelişmekte olan

ülkelerde ise %5 oranında azaltabileceğini öne sürüyor (Sunstein, 2006). Makro düzeyde iklim hedeflerine ulaşılması, enerji verimliliğini ve yerel temiz enerji üretimini artıracak ve endüstriyel enerji maliyetlerini azaltacaktır. Ayrıca iklim bağlantılı hastalıklardan kaynaklanan sağlık maliyetleri ve doğal afetlerden kaynaklanan zararların da azalması beklenmektedir.
Hükümetler, önemli emisyon düşüşlerini elde etmek için karbon salan teknolojileri ortadan kaldırmaya ve tüm sektörlerde fosil yakıtları aşamalı olarak durdurmaya odaklanmalıdır (Climate Action Tracker, 2023). Ülkeler, derin emisyon kesintilerine yönelmeleri halinde ekonomik yarışta geride kalmaktan korkmaktadır. Ancak Çin ve Hindistan gibi hızla gelişen ülkeler bile Paris Anlaşması kapsamında önemli iklim hedefleri taahhüt etmişlerdir. Bu ülkeler artık temiz enerji sektöründe rekabet ederek bu "engeli" fırsata dönüştürmenin yollarını bulmaya çalışmaktadır (Sunstein, 2006).

Uluslararası anlaşmaların bağlayıcı olmaması ve gönüllülük esasına dayalı olması nedeniyle etkisiz olduğu yönündeki tartışmalar yenilikçi yaklaşımları teşvik etmiştir. Karbon vergileri, iklim değişikliğiyle mücadelede en popüler politika aracı olarak kabul edilmektedir. Ancak ülkelerin tek taraflı olarak etkili sonuçlara ulaşabilmesi için kapsamlı bir politika portföyüne ihtiyaç vardır. Geri bildirim mekanizması oluşturan bağlayıcı ticaret tedbirlerinin etkili olduğu ve çok taraflı bir süreci teşvik ettiği kanıtlanmıştır. Montreal Protokolü'nün hidro-floro-karbonlara ilişkin hedeflerinde görüldüğü gibi, sera gazı emisyon hedeflerine ulaşamayan ya da bu hedefleri edinmeyen ülkelere ticaret engelleri gibi cezalar uygulayan bağlayıcı bir anlaşma gereklidir. Böyle bir çerçeve Nobel ödüllü William Nordhaus'un İklim Kulübü fikrine benzetilebilir.

İklim değişikliğinin azaltılması, tüm ülkelerin, özellikle de Çin ve ABD gibi başlıca sera gazı salınımına sebep olan ülkelerin katılımını gerektirmektedir. İklim Kulübü'nde üyelik teşvikleri, uyum maliyetlerinden daha ağır basmalı ve hiçbir üyenin ayrılmak istememesini sağlamalıdır. Nordhaus (2020), bir hedef karbon fiyatlandırma mekanizmasının (salınan karbon tonu başına dolar), yıllık olarak artan küresel karbon fiyatıyla standartlaştırılmış bir ölçüm sağlayarak, hedef emisyon limitlerinden (ton) daha etkili olacağını öne sürmektedir. Ek olarak, kulübe katılmamak üye ülkelere yapılan ithalatta tek tip tarifeler gibi cezalara tabi olmalıdır. Kulüp, Montreal ve Kyoto

Protokollerindeki ülke özelinde farklılaştırılmış taahhütlere benzer şekilde, yine gelişmişlik düzeyine bağlı olarak ülkeye özgü taahhütler belirleyebilir.

Emisyon azaltımlarını finansal açıdan değerli kılmak için Paris Anlaşması'nın esneklik mekanizmaları kapsamında minimum karbon fiyatlarının belirlenmesi gibi tamamlayıcı anlaşmalara ihtiyaç bulunmaktadır. Ancak örneğin Çin'de temiz enerji sektörlerine yapılan önemli yatırımlara rağmen, kömür ve fosil yakıt endüstrilerinin güçlü etkisi nedeniyle karbon fiyatları düşük kalmaya devam etmektedir.

İklim değişikliğine küresel ilgi yoğunlaştıkça yeni yatırım ve finansal mekanizmalar ortaya çıkmaktadır. İklim değişikliğini hafifletme projelerini finanse etmek için IMF'nin Dayanıklılık ve Sürdürülebilirlik Vakfı (RST) kapsamındaki SDR'lerin (Özel Çekme Hakları) kullanılması, iklim davası açısından devrim niteliğinde kabul edilmektedir (Chmielewska ve Sławiński, 2021). IMF üyesi ülkelerin resmi rezervlerini desteklemek amacıyla 1969 yılında oluşturulan SDR'ler, uygun fiyatlı uzun vadeli finansman sağlaması ile bilinmektedir. Başlıca para birimlerinden oluşan bir sepet (ABD doları, Euro, Çin Yuanı, Japon Yeni, İngiliz Sterlini) ile tanımlanan SDR'ler, finansal likiditeyi kolaylaştırır. Bu mekanizmalar ulusal iklim politikalarının tasarımını ve uygulamasını kolaylaştırmaktadır.

Paris Anlaşması, ülkelerin ve hükümetler arası kuruluşların temiz kalkınma endüstrisini yalnızca yük paylaşımı olarak değil, yeni bir büyüme alanı olarak algılama biçiminde yapısal bir değişikliği teşvik ederek bu gelişmeleri tetiklemiş olabilir. Yenilenebilir enerjiye yönelik devlet desteği, yenilenebilir elektriğe yönelik vergi sübvansiyonları ve fosil yakıtlara yönelik yüksek karbon fiyatlandırması sayesinde, yenilenebilir enerjinin maliyeti geleneksel enerjiye göre çok daha düşük hale gelmiştir.

Literatür ve uluslararası anlaşmalar, temiz enerjiyi desteklemenin yenilikçi ve etkili yollarına olan ihtiyacı vurgulamaktadır. Ancak temiz enerji sektörünün emisyonların azaltılması üzerindeki genel etkisi konusunda şüpheler devam etmektedir. Güneş panelleri ve rüzgar türbinlerinin üretiminin gerçekten çevre dostu olup olmadığı, elektrik dağıtım zorluklarının üstesinden gelmenin ne kadar süreceği ve temiz enerji sistemlerinin etkili bir şekilde işleyip işlemediği gibi sorular cevaplanmayı beklemektedir. Bu sorular kapsamlı bir araştırmayı gerektirmektedir ve çevre ve enerji ekonomisinde gelecekteki çalışmaların merkezinde yer almalıdır.

Bölüm 3: Temiz Kaynaklardan Elde Edilen Birincil Enerji Tüketiminin Kalıcılık Özelliklerinin Asimetriler ve Yapısal Kırılmalar Dikkate Alınarak Modellenmesi

Üçüncü bölümdeki çalışma Fransa, Brezilya, Almanya, Japonya ve İngiltere için temiz enerji tüketiminin toplam birincil enerji tüketimi içindeki paylarında 1950-2020 döneminde ülkeye özgü gelişmeleri incelemektedir. Bu ülkeler, yavaşlayan nükleer enerji tüketim seviyeleriyle temiz enerji tüketiminde lider konumdadır. Temiz enerji sektöründeki gelişmelerin ilk iki sırayı süreklilikle koruyan Çin ve ABD üzerindeki etkisini de yakalamak amacıyla analizin ülke grubuna bu iki ülke de eklenmiştir. Temiz enerji bileşenleri, yenilenebilir enerji ve nükleer enerji ayrı ayrı ve karşılaştırmalı olarak incelenerek ülkelere ve enerji kaynaklarına özgü yorum ve politika önerileri yapılmasına olanak sağlanmıştır. Çalışmada kullanılan yöntem hem keskin hem de yumuşak yapısal kırılmaların etkilerini hesaplamaktadır. Aşağıdaki metinde ülkeler özelinde gerçekleşen gelişmeler sonucu tespit edilen yapısal kırılmalar özetlenmiştir. Daha sonra serilerin uzun hafıza özelliklerinin belirlenmesi için uygulanan Modifiye edilmiş Kantil Birim Kök Testinin sonuçları açıklanmaktadır.

Çin

Çin'in yenilenebilir enerji payı serisinde kırılma tarihi olarak 2003 yılı Çin ekonomisindeki yapısal değişimle paralellik göstermektedir. Çin ekonomisi 2000'li yılların başında hızlı bir büyüme evresine girerken, sanayi sektörünün enerji talebi de artmıştır. 2002 yılında Kyoto Protokolü'nün imzalanması yenilenebilir enerji sektörünün gelişimini daha da hızlandırmıştır. 2003 yılında yenilenebilir enerji tüketimindeki kırılma ekonomideki bu yapısal değişimi yansıtıyor. 2011 yılındaki kırılma tarihi Fukuşima felaketiyle doğrudan ilgili olmayabilir, zira bu tarihte nükleer enerji payları azalmamıştır.

Ancak Fukuşima felaketi, Çin'in nükleer enerji konusunda daha ihtiyatlı hale gelmesi nedeniyle yenilenebilir enerji tüketimini hızlandırmış olabilir. Çin hükümetinin 2011 yılında hidroelektrik ve nükleer enerji de dahil olmak üzere temiz enerjiyi teşvik eden 12. Beş Yıllık Planının yayımlanması, 2011 yılından itibaren yenilenebilir enerji tüketimindeki artışa daha da katkıda bulunmuştur.

Nükleer enerji serisinin payında, Çin'deki ilk iki kırılma tarihi, birinci dalga reaktörlerin (Daya Bay ve Qinshan-I) ve ikinci dalga reaktörlerin (Ling Ao ve Qinshan-II&III) 1994 yılındaki ticari işletme tarihlerine denk gelmektedir. 2007 yılından itibaren üçüncü dalga reaktörler döneminin başlamasıyla birlikte kademeli bir artış yaşanmaktadır. Ancak 2007 yılındaki artış daha sonraki yıllara göre çok fazla olmadığı için bir kırılma tarihi olarak tespit edilmemiş olabilir. Üçüncü dalga reaktörlerden sonra nükleer enerji kullanımı, özellikle Fukushima felaketiyle birlikte yavaşlamıştır. 2011 yılı sonrasında yenilenebilir enerji tüketiminde hızlı bir artış görsek de nükleer enerji tüketiminde benzer bir artış gözlemlemiyoruz. Bu durum Fukuşima felaketinin etkisine bağlanabilir. Fukuşima'dan kısa bir süre sonra Çin Devlet Konseyi yeni nükleer santrallere yönelik onayları askıya alma kararı almıştır. Ancak endüstriyel üretime büyük ölçüde bağımlı bir ülke olan Çin, nükleer enerjiden tamamen vazgeçemezdi. 2011 yılında “Nükleer Güvenlik ve Radyoaktif Kirliliğin Önlenmesi ve 2020 Vizyonu için 12. 5 Yıllık Plan”ın onaylanması, nükleer enerjiye dönüş anlamına gelmekteydi. 2013 yılından itibaren üçüncü dalga reaktörlerin faaliyetleri hızlanarak, sonraki yıllarda önemli kapasite artışları sağlanmıştır.

Serinin modellemesine yumuşak kırılma terimlerinin dahil edilmesi, Çin için kırılma tarihlerinin daha doğru tespit edilmesine yardımcı olmuştur. Yenilenebilir enerji payı serisinde 2011 yılındaki kırılma, önemli olaylar ve politika değişiklikleriyle uyumlu olup, yapısal bir değişime dair kanıt sunmaktadır. Nükleer enerji payı serisinde daha belirgin olan 2003 kırılma tarihi, yumuşak kırılmalar dahil edilmeden tespit edilememektedir; bu da analizde hem keskin hem de yumuşak kırılmaların dikkate alınmasının önemini vurgulamaktadır.

ABD

Amerika’da 2000 yılı, OPEC üyelerinin petrol üretim kotalarını düşürmeye karar vermesiyle enerji sektörü için önemli bir yıl olmuştur. Bu kararın dünya çapında da etkileri olmuş ve yeni enerji santrallerinin onaylanmasında yaşanan gecikmeler nedeniyle 2000-2001 Kaliforniya elektrik krizine yol açmıştır. Bu krizin ekonomik sonuçları Kaliforniya sınırlarının ötesine yayılmıştır. Yenilenebilir enerji kaynaklarının payı başlangıçta petrol tüketimindeki azalmaya bağlı olarak artmış, ardından yabancı petrole bağımlılığı azaltmak amacıyla yenilenebilir enerji tüketimini teşvik eden bir dizi politika, yenilenebilir enerji sektöründe yapısal bir değişikliğe yol açmıştır. Bir enerji kriziyle karşı karşıya kalan hükümet, yenilenebilir enerji kaynaklarına daha fazla yatırım yapmaya karar vermiş ve bu da 2000 yılından bu yana genel enerji arz yapısında bir değişikliğe yol açmıştır. 2001 yılında Ulusal Enerji Politikasının geliştirilmesi, güvenilir, uygun maliyetli ve çevresel açıdan sağlam bir enerjisi üretim ve dağıtım sürecini teşvik etmeyi amaçlamıştır.

Amerika Birleşik Devletleri'nde nükleer enerji payının grafiği genel olarak düzgün bir yapı sergilemektedir. İlk nükleer reaktörün inşasına 1968 yılında başlanmıştır ve ülkede şu anda faaliyette olan 92 nükleer reaktör bulunmaktadır. Bunların tamamı 1974 ile 1993 yılları arasında ticari işletmeye geçmiş reaktörlerdir. Petrol krizi sırasında ABD, petrolün yerine nükleer enerjinin geliştirilmesine öncelik vermeyi seçmiştir. Ancak 1979'daki Three Mile Adası kazasından sonra yeni nükleer reaktör inşası bir süreliğine durdurulmuştur. Daha sonraki kapasite artışı devam eden projelerin şebeke bağlantısı nedeniyle olan artışlar olabilir.

Yumuşak kırılma terimleri dahil edildiğinde, ABD eğrisinin düzgün yapısı yüksek bir Fourier frekansı ile iyi bir şekilde hizalanmaktadır. Bu sonuç mantıklıdır çünkü ABD'de nükleer enerjinin sistematik olarak ticarileştirilmesi belirli bir döneme yayılmıştır. Ülke başlangıçta düşük kapasiteli reaktörlerle başlamış ve giderek daha yüksek kapasiteli reaktörler geliştirmiş, aynı zamanda mevcut reaktörlerin kapasitesini de geliştirmiştir. Dünya Nükleer Birliği'nin bir raporu, ABD nükleer sektöründeki performans artışlarının 1998 yılında birleşme ve satın almalar nedeniyle hızlanmaya başladığını göstermektedir.

Yumuşak kırılma senaryosunda keskin kırılma tarihi olarak 1998 yılı tespit edilebilmektedir. İlginçtir ki 1998 yılı aynı zamanda ABD'nin Kyoto Protokolü'nü imzaladığı yıl olmuştur. 1997 yılındaki düşüş, yaklaşık 1000 MWe kapasiteli bir reaktörün kapatılmasına bağlanabilir. Genel olarak, yumuşak kırılma terimlerinin dahil edilmesi, Amerika Birleşik Devletleri'nde hem yenilenebilir enerjinin hem de nükleer enerjinin payına ilişkin serideki kırılma tarihlerinin daha iyi anlaşılmasına ve tespit edilmesine olanak sağlamaktadır.

Fransa

Fransa örneğinde, kırılma tarihleri 2005 ve 2015 olup, bu durum Kyoto Protokolü ve Paris Anlaşması'nın etkisini açıkça göstermektedir. Fransa 1998 yılında Kyoto Protokolü'nü imzalamasına rağmen yenilenebilir enerjiyi teşvik edecek politikalar hemen ortaya çıkmamıştır. Kyoto Protokolü, Rusya ve Kanada'nın onaylanmasının ardından 2005 yılında dünya çapında yürürlüğe girmiştir. Annex I dönemi 2008'den 2012'ye kadardır ve Fransa'nın Kyoto taahhütlerine ilişkin eylem planı "İklim Planı 2004-2012"de ifade edilmiştir. Fransa'nın seçilmiş serilerindeki keskin artışın da gösterdiği gibi, 2005'ten sonra etkili politikalar uygulamaya konulmuştur.

Fransa, Kyoto Protokolü ilkelerini kabul etmiş, geliştirip benimsemiş ve 2015 yılında Paris Anlaşması'nın imzalanmasına ev sahipliği yapmıştır. 2014 yılında Fransız hükümeti, vergi kredileri ve düşük faiz yoluyla yenilenebilir enerji kaynaklarını teşvik eden 13,4 milyar dolarlık bir kredi yasasını kabul etmiştir. Böylece Paris Anlaşması ve rüzgâr enerjisi teşvik politikalarının uygulamaya konulmasıyla birlikte 2015 yılında bir kırılma daha yaşanmıştır.

Fransa, karbon emisyonlarını 2050 yılına kadar %75 oranında azaltmak gibi iddialı bir hedef belirledi ve yüksek nükleer enerji kullanımı sayesinde, diğer ülkelerle karşılaştırıldığında bu hedefe ulaşmaya daha yakın olduğu söylenebilir. Petrol krizinin ardından 1977 yılında ilk nükleer reaktörünü kuran Fransa, sektöre önemli yatırımlar yaparak 1980 öncesinde toplam 34.900 MWe kapasiteye ulaştı. Ancak 1980'li yılların sonuna gelindiğinde nükleer enerji kapasitesi ve talebinin azaldığı anlaşıldı. Bu da yatırımların yavaşlamasına neden oldu. Sonraki yıllarda, gerekli olan maliyetli yenilemeler ve nükleer güvenlik endişeleri nedeniyle nükleer enerji üretimi önemli bir artış göstermedi. Ayrıca Avrupa genelinde nükleer enerjiye karşı muhalefetin 2000'li yıllarda iktidardaki hükümetler üzerinde de etkisi oldu.

Brezilya

Brezilya örneğinde, petrol krizi sırasında yenilenebilir enerjiye yumuşak geçiş ve 2002 ekonomik krizi sonrasında (aynı zamanda protokolün imza tarihi) Kyoto Protokolü'ne verilen hızlı tepki açıkça görülmektedir. 2002 öncesi dönem, 1970'lerdeki petrol krizinin ardından yenilenebilir payların kademeli olarak artması ve Brezilya'nın ilk nükleer reaktörünün şebekeye bağlanmasının ardından yenilenebilir payların eğiliminin yumuşak bir şekilde azalmasıyla düzgün bir yapı sergilemektedir. Yumuşak kırılmaları dikkate almadan yapısal kırılmaların kesin tarihlerini tahmin etmek zordur. Ancak yumuşak kırılma terimleri de eklendiğinde, 1975'teki petrol krizi ve 2002'de Kyoto Protokolü'nün imzalanmasıyla yaşanan toparlanmanın ardından yaşanan büyük kırılmalar tespit edilebiliyor.

2000'li yıllarda Brezilya'nın enerji sektörünün yaklaşık %20'si yenilenebilir enerjiye bağlıydı ancak daha sonra nükleer enerji tüketimindeki artışın yanı sıra yenilenebilir enerji tüketiminde de bir düşüş görüyoruz. Yenilenebilir enerji kaynaklarının payındaki azalma, büyük olasılıkla, Brezilya'da 2002 civarında yaşanan ekonomik yavaşlama sırasında endüstriyel yenilenebilir enerji tüketiminin yavaşlaması ve 2001 yılında büyük bir nükleer reaktörün şebekeye bağlanmasının ardından nükleer enerji tüketiminin toplam birincil enerji tüketiminde daha büyük bir pay işgal etmesinden kaynaklanmıştır.

Brezilya'da nükleer enerji tüketimi 1982-1984 yıllarında, ilk reaktörü Angra I'in şebekeye bağlanma döneminde başlamıştır. Ancak Angra I, ilk yıllarında buhar tedarikindeki sorunlar nedeniyle bir süreliğine kapanmak zorunda kalmıştır. Brezilya'nın 1964 ile 1985 yılları arasındaki askeri hükümeti istikrarsızlıkla bağdaştırılmakta ve ülkenin 1980'lerdeki "kayıp on yıl" olarak bilinen eşit derecede istikrarsız ekonomisi ve 1994 başkanlık seçimlerine kadar yaşanan siyasi çalkantılar, Brezilya'nın tek nükleer reaktörünün tam olarak çalışmasını engellemiştir.

1993'teki düşüş kötü yönetime bağlanabilir. 2000 yılında ikinci nükleer reaktörün şebekeye bağlanmasının tespit edebiliyoruz. Uyguladığımız testle 2000 yılını yapısal kırılma olarak belirleyemediğimiz halde 2001 yılını görebilmemizin nedeni muhtemelen 2000 yılının şebekeye bağlantı tarihi, 2001 yılının ise ticari işletmeye başlama tarihi olmasıdır.

Almanya

Almanya'nın artan yenilenebilir tüketime geçişi diğer gelişmiş ülkelere göre daha geç başlamıştır. Yenilenebilir enerji tüketimindeki ilk önemli artış 1995 yılında, Kyoto Protokolü'nden hemen önce görülmüştür. 1995'ten önce Almanya'da çoğunlukla hidroelektrikten elde edilen yenilenebilir enerji kullanımı düşük ancak istikrarlı bir süreç sergilemekteydi. 1990'dan 2010'a kadar olan dönem Almanya'da "biyoenerji patlaması" olarak bilinmektedir. 1995 yılındaki kırılma belirli bir olaya denk gelmese de yenilenebilir enerji payındaki ilk yükseliş eğilimini temsil etmektedir.

1986'daki Çernobil kazasından sonra Almanya nükleer enerji konusundaki tutumunu büyük ölçüde değiştirmiştir. Kaza alanının Almanya sınırına yakın olması, kamuoyunda radyoaktif bir bulutun Kuzey Almanya'ya yayıldığı algısına yol açtı. Nükleer enerjiyi aşamalı olarak durdurma kararı 2000 yılında alınmıştı; ülkenin aynı zamanda Kyoto Protokolü tarafından belirlenen hedeflere de ulaşması gerekmekteydi. Nükleer enerjinin payı 2000 yılından sonra artmamaktadır. Endüstriyel bir güç merkezi olan Almanya'nın, enerji taleplerini karşılamak için hızla nükleer enerjiden uzaklaşırken başka enerji kaynaklarına yönelmesi gerekmekteydi. Yenilenebilir enerjinin payı Kyoto Protokolü öncesinde zaten yükselişteydi. Protokolün imza tarihini takiben, 2003 yılında seride bir kırılma tespit edilebilmektedir. Bu aşamada zaten nükleer enerjiyi aşamalı olarak durdurma sürecinde olan Almanya ancak Fukuşima felaketi ile sekiz nükleer santralini derhal kapatmıştır. Bu karar nükleer yanlısı parti liderliğindeki Alman parlamentosu tarafından bile oylanmıştır. Bu nedenle 2011 yılında Almanya'nın yenilenebilir enerji payı grafiğinde bir kırılma tarihi görebilmekteyiz.

Şekil 3.4.2'de, 1984 yılında Almanya'nın nükleer enerji serisinde keskin bir artış gözlemlemekteyiz. Almanya'da nükleer enerjinin teşvik edildiği bu aşamada, 1984 yılında üç yeni yüksek kapasiteli nükleer santral şebekeye bağlanarak nükleer enerji tüketimi önemli ölçüde artmıştır. 1986'nın (Çernobil) bir kırılma tarihi olarak tespit edilememesinin nedeni muhtemelen 1984'e çok yakın olması ve BP (Bai-Perron) sürecinin kırpma aralığına girmesi olabilir. Yumuşak kırılmalar dikkate alınmadığında 2011 bir kırılma tarihi olarak tespit edilememiştir.

Japonya

Japonya'da 1960'lı yıllardaki hızlı büyüme döneminde yenilenebilir enerji kaynaklarının bol olmasıyla birlikte toplam enerji tüketimi de artmıştır. Sonuç olarak bu dönemde yenilenebilir enerji kaynaklarının payı azalmıştır. Japonya'da Kyoto Protokolü ve ilk taahhüt dönemi (2008-2012) ile ilgili değişiklikler kademeli bir şekilde gerçekleşmiştir. Anlaşmanın 2002 yılında imzalanmasının ardından politikaların oluşturulması ve politika hedeflerinin gerçekleştirilmesi zaman almıştır. Japonya'nın nükleer enerji sektörü sağlam temellerle kurulmuştu. Bu durum yenilenebilir enerjiye daha yavaş bir geçişe neden olmuş olabilir (Ohta, 2020). 2011'deki Fukuşima felaketini takip eden keskin kırılmanın kesin tarihi, yumuşak kırılmalar dahil edilmeden yakalanamamıştır.

2011'de gözlemlenen önemli ve keskin düşüş nedeniyle, yumuşak kırılmaların dahil edilmesi, verilerdeki diğer keskin kırılmaların doğru şekilde modellenmesini zorlaştırmış olabilir. Örneklemi 1950-2011 ve 2011-2020 olarak iki kısma ayırdığımızda, 1978'de petrol krizine karşılık gelen bir kırılma ve Tokyo Elektrik Enerjisi Şirketi'nde meydana gelen bir nükleer güvenlik skandalı nedeniyle 2003'teki düşüşü tespit eden bir kırılma bulunması mümkündür. Bu olaylar, örneklemin tamamına bakıldığında 2011'deki keskin kırılmanın gölgesinde kalan farklı örüntüler sergileyebilir.

Birleşik Krallık

Birleşik Krallık, Kyoto Protokolü'nün ilk taahhüt döneminin (2008-2012) ardından yenilenebilir enerji politikalarında yumuşak bir geçiş yaşamıştır. 2008 yılında İklim Değişikliği Yasası'nın ve 2009 yılında Yenilenebilir Enerji Yasası'nın uygulamaya konması, yenilenebilir enerji üretimini teşvik etme yönünde önemli adımlardır. Ancak yenilenebilir enerji tüketiminde keskin bir kırılmanın 2010 yılı civarında görülmesi, üreticilere yönelik garantili ödeme ve teşviklerin uygulanmaya başladığı yılı işaret etmektedir. Birleşik Krallık'ın yenilenebilir enerji sektöründeki kademeli değişiklikleri yakalamak ve 2010'daki keskin kırılmayı tespit etmek için modelleme sürecine yumuşak kırılma terimlerini dahil etmek çok önemlidir.

Birleşik Krallık'ın nükleer enerji sektörü, 1989 ile 1995 yılları arasında beş elektrik santralinin ticari işletmesiyle bir büyüme dönemi yaşamıştır. 1992'deki kırılma bu genişleme dönemini temsil etmektedir. Ancak 2000'li yıllarda nükleer enerji, maliyet-fayda analizi ve enerji güvenliği gibi faktörler dikkate alınarak siyasi tartışma konusu haline gelmiştir. 2002 yılında hükümet yeni nükleer santrallerin inşasını durdurma kararı almıştır.

İngiltere hükümetinin 2008 yılında nükleer enerji yatırımlarına yeşil ışık yakması, 2009 yılında nükleer enerji tüketiminin artmasına neden olmuştur. Özellikle iklim kaygıları ve Fukuşima nükleer felaketinin etkisine yanıt olarak yenilenebilir enerji kaynaklarının desteklenmesine yönelik değişim ve nükleer enerjinin genişletilmesine yönelik tereddüt, Birleşik Krallık'ta nükleer enerji paylarında süregelen düşüşü açıklayabilir.

Temiz enerji sektöründeki tarihi olaylar, yenilenebilir ve nükleer enerji serilerinin paylarının istatistiksel bileşenlerinde şoklar yaratmaktadır. Bu olaylara verilen kalıcı tepkiler, bilinçli endüstriyel ve politik kararlar için çok önemlidir. Üçüncü bölümdeki çalışmada yukarıda değerlendirilen her ülkedeki temiz enerji bileşenlerinin uzun hafıza özellikleri hem keskin hem de yumuşak yapısal kırılmalar dikkate alınarak incelenmekte ve bu şokların asimetrik etkileri Kantil Birim Kök (QUR) Testi prosedürleri kullanılarak analiz edilmektedir. Bu bölümde temiz enerji serisine yönelik geçici şokların ülkeye ve kaynağa özel olarak hem kalıcı hem de geçici etkilere yol açtığı tespit edilmiştir. Yapısal kırılmalar devreye girdiğinde, özellikle hafif şoklara karşı olmak üzere daha fazla durum karşısında uzun hafıza yerine geçici tepkiler görmekteyiz.

Kırılmaları dikkate almayan geleneksel birim kök testi hiçbir ülkede birim kök hipotezini reddedememektedir. Tek yapısal kırılmaya sahip ZA Testi, yalnızca

ABD'nin yenilenebilir enerji payı için durağanlığı tanımlarken, iki yapısal kırılmaya izin veren LS Testi, yapısal kırılmaların dahil edilmesinin, aksi takdirde durağan olmayan değişkenler için durağanlığa yol açabileceği iddiasını daha açık bir şekilde desteklemektedir.

LS Testi, Japonya'nın yenilenebilir enerji kaynaklarının payı ve Fransa, Almanya ve Birleşik Krallık'ın nükleer enerjinin payı dışında durağanlık bulmuştur. EL Testi hiçbir durumda durağanlık bulamamaktadır. Ayrıca bu testlerde bulunan kırılma tarihleri de bu serilerdeki tarihsel gelişmelerin zamanlaması ile örtüşmemektedir. Birden fazla bilinmeyen yapısal kırılmaya yönelik BP Testi sonuçları daha iyi tahminler bulmuştur. BP prosedürüne düzgün kırılma terimlerinin dahil edilmesiyle serinin daha doğru modellenmesi sağlanmıştır.

QUR Testi, bir serinin tüm olasılık dağılımını araştıran uzun hafıza davranışının dinamiklerini daha derinlemesine incelemeye olanak tanır. Sonuçlar, QUR yapısal kırılmalar olmadan uygulandığında ne yenilenebilir enerji paylarında ne de nükleer enerji pay serilerinde durağanlık tespit edemediğimizi göstermektedir. Bu çalışmada, alternatif hipotezde yumuşak ve keskin kırılmalar kullanılarak değiştirilmiş QUR Testinde her bir kantil için önceden bilinmeyen kırılma parametreleri belirlenmiştir. Her bir kantildeki yapısal kırılmaların, modelin deterministik kısmından arındırılmadan birim kök testi prosedürüne dahil edilmesi, bu kırılmaların serinin asimetrik kalıcılık davranışı üzerindeki etkisinin daha iyi tespit edilmesine olanak tanır. Bu çalışmada Modifiye edilmiş QUR Testi ile ülkeye özgü ve temiz enerji kaynağına özgü durağanlık davranışları incelenmektedir.

Modifiye edilmiş testin sonuçlarına göre, Fransa ve İngiltere'nin yenilenebilir enerji payları herhangi bir dilim için kırılmalar getirildikten sonra bile durağanlık göstermemiştir. Çin, ABD ve Japonya'da birim kök, en yüksek ve en düşük dilimler için değiştirilmiş QUR testi ile reddedilememektedir, bu da yenilenebilir enerji serilerine yönelik yüksek pozitif ve yüksek negatif şokların kalıcılık gösterdiği anlamına gelmektedir. Çin ve Japonya için de 0,1 yüzdelik dilim durağan bulunmuştur. Büyük negatif şoklara karşı bu geçici davranışın nedeni, Çin ve Japon hükümetlerinin bu şoklara karşı önlem alarak yenilenebilir enerji tüketimini önceki gelişimsel sürecine döndürmesi olabilir. Almanya'da yenilenebilir enerji serisinin payında yalnızca pozitif şoklar kalıcılık göstermektedir. Brezilya'da olumlu şoklar tüm düzeylerde geçici, olumsuz şoklar ise kalıcı bulunmuştur.

Nükleer enerji payları serisi, modifiye edilmiş test ile her ülkedeki belirli yüzdelikler için durağanlık gösterirken, geleneksel QUR Testi birim kök ile sonuçlanmaktadır. Çin için yüksek pozitif şoklar kalıcı, Fransa için ise tüm pozitif şokların etkisi kalıcıdır. ABD'de 9'uncu dilim hariç pozitif şoklar kalıcı, negatif şokların tümü geçicidir. Sonuçlar, bu ülkelerin nükleer enerji sektöründe herhangi bir gerileme riskini kabul etmediğini, ancak pozitif şoklara izin verildiğini göstermektedir. Almanya ve Brezilya'da ise yüksek negatif şoklar varlığını sürdürmektedir.

İngiltere ve Japonya'da tüm olumsuz şoklar kalıcıdır. Bu ülkelerin nükleer enerji sektörleri düşüş eğilimdedir. Japonya'da tüm pozitif şoklar geçici, İngiltere'de ise yüksek pozitif şoklar kalıcı bulunmuştur. Nükleer enerji serisinde pozitif şokların geçici, negatif şokların ise kalıcı davranışı özellikle Fukuşima'dan kaynaklanmaktadır.

Pozitif şoklar geçiciyse, hükümetlerin temiz enerji tüketimini artırmak için uzun vadeli yenilenebilir portföy standartları ve tarife teşvikleri gibi sürekliliği olan pozitif şokları seçmesi gerekmektedir. Pozitif şokların kalıcı olması durumunda, planlanan miktarda temiz enerji üretimi için sabit ikramiyeler gibi tek seferlik pozitif şoklar yeterlidir. Pozitif şokların kalıcı olması durumunda, eğer hükümetler ve sektör temiz enerji tüketimindeki payın artmasını istiyorsa, bu negatif şoklardan kaynaklanan kayıpları telafi etmek için olumlu şoklarla karşılık vermeleri gerekmektedir. Politikalar pozitif şokların uzun hafıza davranışına göre tasarlanmalıdır. Eğer bir ülkede nükleer enerji kademeli olarak kaldırılmak isteniyorsa, negatif şoklara karşı nükleer enerji pay serilerinin uzun hafıza özelliklerini de göz önünde bulundurarak hareket edilmelidir.

Nükleer tüketimdeki düşüş öncelikle nükleer kazalara bağlanmaktadır. Nükleer enerjiyi güvensiz bulan ülkeler, odaklarını yenilenebilir enerjiye kaydırmıştır. Bu durum da yenilenebilir enerji kaynaklarının payında artışa yol açmıştır. Kyoto Protokolü'nün nükleer enerji için değil de özellikle yenilenebilir enerji için bir kırılma tarihi olarak görülmesinin nedenlerinden birinin de bu olduğunu belirtmek gerekmektedir. Enerji tüketiminin geleceği muhtemelen çok çeşitli teknolojilere bağlı olacaktır, ancak temiz enerji kaynaklarının, özellikle de yenilenebilir enerji kaynaklarının önemli ölçüde daha büyük bir pay oluşturması beklenmektedir. Petrol ve gaz şirketlerine uygulanan vergiler, yatırım stratejileri ve hava taşımasında utandırma (flight shaming) gibi girişimler hükümetler arası politikalar ve kurumsal kararlar, temiz enerji sektöründeki teknolojik yeniliklerin hızlandırılmasında çok önemli bir rol oynamaktadır.

Temiz enerji pay serilerinin tüm dağılımının birim kök özelliklerini test eden QKS Testi ile elde ettiğimiz bulgular, yapısal kırılmalar dikkate alındığında yalnızca üç durumda durağanlık elde edildiğini göstermektedir. Almanya'nın yenilenebilir enerji payı ve nükleer enerji payı serileri ile Fransa'nın nükleer enerji payı serisi. Bu iki ülke için elde edilen durağanlık bu ülkelerin kurumsal gelişmişlik düzeyleri ile açıklanabilir. Bulgularımız, bu dinamiklerin tam olarak anlaşılabilmesi için ülkeye özgü çalışmaların yapılmasının önemini vurgulamaktadır.

Herhangi bir enerji değişkeninin şoklara karşı kalıcı tepkisi, dolaylı etkileri nedeniyle de büyük önem taşımaktadır. Temiz enerji değişkenlerine yönelik şoklar, geleneksel enerji kullanımında, genel ekonomik çıktılarda, istihdam oranlarında ve çevresel göstergelerde önemli değişikliklere yol açabilir. Enerji ve enerji dışı değişkenler arasındaki bu karmaşık korelasyon, bir alandaki yüksek kalıcılığın diğer alanda da yüksek kalıcılıkla sonuçlanabileceği anlamına gelmektedir. Eşbütünleşme üzerine yapılan çok sayıda çalışma, enerji değişkenlerinin enerji dışı değişkenlerle uzun vadeli bir ilişki paylaştığını göstermiştir. Meng ve diğerleri (2013), son çalışmaların gelişmiş ülkelerde ekonomik büyüme ile enerji tüketimi arasında negatif bir korelasyon bulduğunu, gelişmekte olan ülkelerde ise korelasyonun pozitif eğilimde olduğunu belirtmiştir. Bu durum gelişmiş ülke ekonomilerinin enerji şoklarına karşı giderek dirençli hale geldiğini göstermektedir.

Gelecekte temiz enerji serilerinin uzun hafıza özellikleri ile ilgili çalışmaların ülkeye özgü ve kaynağa özgü analizlere daha fazla odaklanması önerilmektedir. Veri erişilebilirliği durumunda, 2008 ekonomik krizinin, COVİD-19'un ve Rusya-Ukrayna savaşının temiz enerji serisi üzerindeki etkilerinin incelenmesi faydalı bilgiler ortaya çıkaracaktır. Kalıcılık parametresinin değişmesine izin veren, yapısal kırılmaların etkisini bu parametre üzerinde de gözlemleyen testler de yeni bilgiler sağlayabilir. Ayrıca, her bir temiz enerji bileşeni ile çevresel bozulma arasındaki eşbütünleşmeyi araştıran ülkeye özgü çalışmalarda da bir boşluk bulunmaktadır. Bu tür çalışmalar, bu serilere gelen farklı şokların ortak etkilerle sonuçlanıp sonuçlanmayacağını görmeye yardımcı olacaktır.

Bölüm 4: CO_2 Emisyonları ile Temiz Enerji Tüketimi Arasında Zamana Göre Değişen Eşbütünleşme İlişkisi

Dördüncü bölüm, yumuşak rejim değişikliklerini hesaba katan zamanla değişen bir eş bütünleşme analizi kullanarak, yenilenebilir enerji ve nükleer enerjiyi ayrı temiz enerji bileşenleri olarak inceleyerek emisyon literatürüne katkıda bulunmaktadır. Mevcut çalışmalarda bu bileşenler zamanla değişmeyen eşbütünleşme yöntemleriyle analiz edilmiş olsa da biz zamanla değişen analizin önemini vurgulamakta ve bu yaklaşımla ilerlemekteyiz. Ayrıca, önceki araştırmalardan farklı olarak, temiz enerjinin hem çevresel hem de ekonomik açıdan etkisini yakalamak için daha doğru bir ölçüm olarak temiz enerji tüketimi paylarını kullanmaktayız.

Bu amaçla, bu bölümde hem gelişmiş hem de gelişmekte olan ülkeler dahil olmak üzere temiz enerji tüketiminin en yüksek olduğu on ülkeye odaklanılarak 1950-2020 dönemine ait veriler eşbütünleşme dikkate alınarak analiz edilmektedir. Bu tarih aralığı, temiz enerji tarihindeki üç önemli olayın etkisini değerlendirmemize olanak tanımaktadır: 1970'lerdeki petrol krizi, 2000'lerdeki Kyoto Protokolü ve 2011'deki Fukuşima Nükleer Felaketi. Bierens ve Martins'in, Chebyshev'in zaman polinomları kullanılarak uyguladığı Zamanla Değişen Eşbütünleşme Testi (2010)'nin uygulamasını yapan çalışmamız bu olayların eşbütünleşme ilişkisi içindeki etkilerini yakalayabilmektedir. Zamanla değişmeyen parametrelerle bir eşbütünleşme (CI) ilişkisinin bulunamadığı ülkeler için (özellikle ABD, Brezilya, Rusya ve Hindistan), Zamanla Değişen Eşbütünleşme (TVC) Testi'nin uygulanması, eşbütünleşmeyi tespit etmektedir. Zamanla değişen parametreler göz önüne alındığında, tüm ülkelerde emisyonlar, temiz enerji payları ve GSYH serileri arasında uzun vadeli ilişkiler bulunmuştur.

Şekil 4.2.2 ve 4.2.3'te sunulan veri analizi, ABD, Fransa, Almanya ve Birleşik Krallık'ta kişi başına emisyon ve kişi başına GSYH artış oranlarında kademeli bir ayrışma olduğunu ortaya koymaktadır. Bu ülkelerde kişi başına düşen emisyon artışı, kişi başına düşen GSYH artışıyla karşılaştırıldığında yavaşlamaktadır. Bu ülkeler için kişi başına emisyonların ve kişi başına GSYH'nin zamanla değişen uzun vadeli parametreleri, genellikle aynı işareti göstermektedir. Bu sonuçlar “göreceli ayrışma” dikkate alındığında TVC Testi parametreleriyle uyumludur.

Fransa, Almanya ve Japonya için nükleer enerji denklemlerinde, artan nükleer enerji paylarının emisyonlar üzerindeki negatif etkisini, Almanya’da serinin genelinde görmekteyiz. Bu etki Fransa'da 2000'li yıllarda, Japonya'da ise 2010'lu yıllarda azalmıştır. Almanya da nükleer tesislerini aşamalı olarak kaldırma sürecindeyken, bu ülkelerin mevcut gidişatlarına göre, emisyon artışında bir azalma, yalnızca GSYH büyümesindeki bir azalma veya yenilenebilir enerjide ve enerji verimliliğinde ciddi bir artış ile sağlanabilir.

Yenilenebilir enerjinin payının, bu çalışmadaki ülkeler için mevcut enerji kullanımı ve ekonomik büyüme trendlerinde emisyonların azaltılmasında uzun vadede önemli bir etkisi olmadığı görülmektedir. Daha yüksek yenilenebilir enerji payının emisyon azaltıcı etkisi yalnızca, analiz edilen diğer ülkelerle karşılaştırıldığında önemli ölçüde daha yüksek yenilenebilir enerji tüketimine sahip olan Çin'de belirgindir.

Sonuç olarak, daha temiz enerji karışımlarına rağmen çoğu ülke fosil yakıtlara bağımlı olmaya devam etmektedir. Zararlı enerji kaynaklarının tüketimi artmaya devam etmekte ve bu da CO_2 emisyonlarının artmasına neden olmaktadır. Artan toplam enerji tüketimi bağlamında, fosil yakıtların yerini yenilenebilir enerji kaynakları almamaktadır. Bunun yerine, yenilenebilir kaynaklar, zararlı enerji kaynaklarına olan bağımlılığı azaltmadan daha fazla enerji tüketmek için kullanılmaktadır. Literatür, 2008 ekonomik krizinin ardından birçok ülkenin odak noktasını çevresel kaygılardan ekonomik önceliklere kaydırdığını göstermektedir. Bu değişim, artan temiz enerji tüketimine rağmen CO_2 emisyonlarının neden azalmadığını açıklayabilir. Ancak değişim her zaman mümkündür. Temiz enerji sektörüne önemli ölçüde odaklanan Çin örneği, diğer ülkelerin de temiz enerjiye, özellikle de yenilenebilir kaynaklara olan ilgilerini artırabileceklerini gösteriyor. Yenilenebilir enerjinin endüstriyel uygulamalar, ulaşım ve konut faaliyetleri de dahil olmak üzere çeşitli sektörlere dahil edilmesi CO_2 emisyonlarının azaltılmasını sağlayabilir. Ayrıca ülkeler atık yönetimi, ormansızlaşma ve tarım gibi diğer yüksek emisyon faktörlerini de ele almalıdır.

Gelecekteki çalışmalarda eşbütünleşme (CI) ilişkisinin hem keskin hem de yumuşak değişikliklere uğramış olabileceği dikkate alınabilir. Çoklu kırılmaları barındıran yeni Eşbütünleşme Testlerinin geliştirilmesinin yanı sıra, eşbütünleşmenin daha incelikli bir şekilde araştırılması gerekmektedir. Ayrıca iklim yönetimi ve enerji sektöründeki gelişmeleri uzun vadeli ilişkilerin asimetrik tepkilerini açıklayan kantil eşbütünleşme çalışmaları alana değerli bilgiler sağlayabilir. Çalışmalar aynı zamanda temiz enerji paylarının yanı sıra enerji verimliliği göstergelerinin de emisyonlar üzerindeki etkisine odaklanmalıdır. Temiz enerji payları ile emisyonlar arasındaki pozitif ilişki, bir ülkenin enerji verimliliği gerekliliklerini göz ardı ettiği anlamına gelebilir fakat bu konuda daha etkili yorum yapabilmek için daha derin araştırmalar gerekmektedir.

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