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A study of Finance-Energy-Environment relationships

Mayssa Mhadhbi

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A study of Finance-Energy-Environment relationships

Une étude des relations entre la finance, l'énergie et l'environnement

Thèse de doctorat de l'université Paris-Saclay et de l'École Supérieure de Commerce de Tunis

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Spécialité de doctorat : Sciences économiques

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sous la direction de **Stéphane GOUTTE**, professeur des université et la co-direction de
Talel BOUFATEH, maître de conférence HDR

Thèse soutenue à Paris-Saclay, le 18 Décembre 2023, par

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Titre : Une étude des relations entre la finance, l'énergie et l'environnement

Mots clés : Développement financier ; Marché du carbone ; Émissions de carbone ; Marché boursier ; Marchés de l'énergie

Résumé : Les relations entre le développement financier, les marchés de l'énergie et les marchés du carbone ont pris une place centrale dans le débat sur la durabilité environnementale et la croissance économique. Cette thèse est le résultat de quatre articles scientifiques, chacun examinant divers aspects de cette relation complexe dans le contexte des pays émergents, de l'Europe et de la Chine. Cette question générale est particulièrement importante, puisqu'elle permet de mieux comprendre comment les dynamiques financières, énergétiques et de carbone interagissent dans différents contextes géographiques, ouvrant ainsi la voie à des solutions plus efficaces pour relever les défis mondiaux. De plus, les quatre articles qui composent cette thèse se complètent en abordant différents aspects de cette problématique, ce qui contribue à une perspective plus nuancée améliorant notre compréhension. Le premier article aborde la notion courante selon laquelle le développement financier aggrave les émissions de CO₂ en stimulant la croissance économique et la consommation des énergies dans les économies en développement. Cependant, nos résultats révèlent que les chocs négatifs sur les marchés boursiers ont un impact plus marqué sur les émissions de carbone que les chocs positifs dans ces pays. Cet article met en lumière la relation asymétrique entre les marchés boursiers et les émissions de carbone. Le deuxième article explore l'interconnexion entre les marchés boursiers, l'énergie et les prix du carbone Européen et Chinois. Cet article met en évidence les effets de débordement à court et à long terme entre

ces marchés. Ces résultats soulignent l'importance du marché chinois du carbone dans la liaison avec son marché boursier, les prix du pétrole et le marché des obligations vertes, tandis que l'Europe présente une relation plus graduelle en raison de son intégration avancée. Le troisième article examine l'impact des chocs pétroliers décomposés sur les marchés du carbone européens et chinois. Cette étude révèle une stabilité du marché du carbone européen et des réactions positives aux chocs de demande et d'offre de pétrole, mais des réponses négatives aux chocs de risque. En contraste, le marché chinois du carbone réagit fortement aux chocs de demande de pétrole en raison de sa dépendance et de sa puissance industrielle. Le quatrième article explore les dynamiques complexes entre les marchés du carbone en Europe et en Chine, ainsi que leurs interactions avec les marchés des combustibles fossiles et les indices d'énergie propre. L'étude met en évidence des modèles d'interconnexion distincts entre ces régions. Le marché chinois du carbone bénéficie de l'effet de débordement en provenance du secteur des énergies fossiles et de l'énergie propre, tandis que le marché européen du carbone est affecté par la volatilité de certains indices d'énergie propre. Ces quatre articles contribuent à une compréhension nuancée de l'interaction complexe entre les marchés financiers et énergétiques, soulignant la nécessité d'adopter des approches personnalisées pour relever les défis du changement climatique et des marchés du carbone dans un monde de plus en plus interconnecté.

Title : A study of Finance-Energy-Environment relationships

Keywords : Financial Development ; Carbon market ; Carbon emissions ; Stock market ; Energy markets

Abstract : The relationship between financial development, energy, and carbon markets has become a key focus of the debate on environmental sustainability and economic growth. This thesis results from four academic articles, each examining different aspects of this complex relationship in the context of emerging markets, Europe, and China. This general issue is of particular importance, as it provides a better understanding of how financial, energy and carbon dynamics interact in different geographical contexts, paving the way for more effective solutions to global challenges. Moreover, the four articles that make up this thesis are complementary in that they address different angles of this issue, thus contributing to a nuanced perspective that enhances our understanding. The first article discusses the common idea that financial development leads to increased CO₂ emissions by fuelling economic growth and dependence on polluting fossil fuels in developing economies. However, our results highlighted that negative shocks in stock markets negatively impact carbon emissions more than positive shocks in these countries. Our findings revealed an asymmetric relationship between stock markets and carbon emissions. The second article investigates the interconnectedness of stock markets, energy, and carbon prices, focusing on the European Emissions Trading Scheme and the Chinese carbon permit trading market. This article highlights short- and long-term spillover effects between these markets. These results highlight that China's carbon market plays a

central role in connecting with its stock market, oil prices, and green bond market. At the same time, Europe exhibits a more gradual and sustained relationship among these markets due to more extended integration and maturity. The third article investigated the impact of decomposed oil shocks (supply, demand, and market-specific risk shocks) on European and Chinese carbon markets. The study reveals that the European carbon market remains stable and exhibits positive responses to oil demand and supply shocks but reacts negatively to risk shocks. In contrast, China's carbon market strongly reacts to oil demand shocks due to its dependency and industrial strength. The fourth and final study explores the complex dynamics between carbon markets in Europe and China and their interactions with the three main fossil fuel markets and several clean energy indices. This study highlights distinct interconnectedness patterns among these regions. The Chinese carbon market receives return spillover from the fossil fuel and clean energy sector, while the European carbon market receives volatility spillover from some clean energy indices. Through these four articles, which contribute to a nuanced understanding of the complex interaction between various financial markets and energy dynamics, this thesis highlights the need for customized approaches to meet the challenges posed by climate change and carbon markets in an increasingly interconnected world.

With deep respect and gratitude to my esteemed supervisor, Professor Mohamed Imen Gallali, who believed in me since 2018 and ignited the spark of research in me, inspiring this thesis and a lasting commitment to the pursuit of knowledge in his memory.

Dedication

Besides my professors, this work is dedicated to everyone who contributed to its success.

To my beloved mother, Sarra, a remarkable woman whose strength, love and sacrifices have been the guiding force of my academic career. From my earliest days, it was you who instilled in me a deep appreciation of knowledge and the value of hard work. Your unwavering support, often at the expense of your own dreams and aspirations, was the foundation on which my academic career was built. Your love and confidence in me have been the pillars of my determination, resilience and success. I dedicate this thesis to you, not only by way of thanks, but also as a profound expression of my infinite gratitude for the sacrifices you have made and the unfailing support you have given me. Your influence on my life is immeasurable, and this achievement is as much yours as it is mine. Thank you, Mom.

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Introduction

The findings of the Intergovernmental Panel on Climate Change (2014) indicated a potential increase of nearly five degrees Celsius in global average temperatures by 2100, accompanied by a rise of around one meter in sea levels. In response, the 2015 Paris Climate Conference convened to address these pressing climate concerns. The conference aimed to establish targets that would effectively limit global temperature rise to below two degrees Celsius (United Nations, 2021a).

In light of these challenges, economists have carried out research to explore the interconnection between various macroeconomic factors and environmental degradation. They aim to identify the elements that could help achieve environmental preservation objectives while supporting economic growth. Among these macroeconomic factors, financial development (FD) emerges as an essential element likely to exert a substantial influence on the environment.

The 21st century has seen a growing number of major political and strategic objectives to improve environmental quality, biodiversity, and socioeconomic well-being by promoting sustainable development. These efforts include the Paris Agreement, which is designed to mitigate climate change while promoting sustainable practices; the United Nations Sustainable Development Goals, which address a range of global challenges from poverty to clean energy; initiatives such as the Convention on Biological Diversity, dedicated to halting biodiversity loss; the transition to renewable energy sources; the promotion of circular economies and green infrastructure; the creation of conservation reserves; sustainable agriculture practices; climate resilience measures; and the promotion of green financing mechanisms. These diverse efforts reflect a concerted global effort to balance human progress with environmental and social sustainability.

As these goals have been adopted, business models have been oriented towards the transition to sustainability. These models aim to address global challenges such as energy crises, inadequate waste management, resource depletion, human and animal welfare concerns, pollution, unhealthy diets, and other related issues. The primary objective is to prevent, manage, and wherever possible, find solutions to these pressing global problems.

In the research field, the predominant focus has been studying the link between economic growth and environmental degradation. A few studies have explored the significant role of financial development and the influence of energy prices. Including this crucial variable in the research, framework is essential because of the significant

attention it has attracted among policy-makers and researchers. This attention has notably increased after the 2008 global financial crisis (Acheampong et al., 2020), as strikingly illustrated in Figure 1, which shows the volume of research since 2007 for articles investigating the complex link between financial development, energy use and carbon. Scientific discussions have highlighted the potential importance of financial development in shaping economic progress and in particular its implications for the environment, especially concerning the dynamics of carbon emissions. However, empirical evidence does not allow us to determine whether the impact on environmental degradation is positive, negative, or neutral.

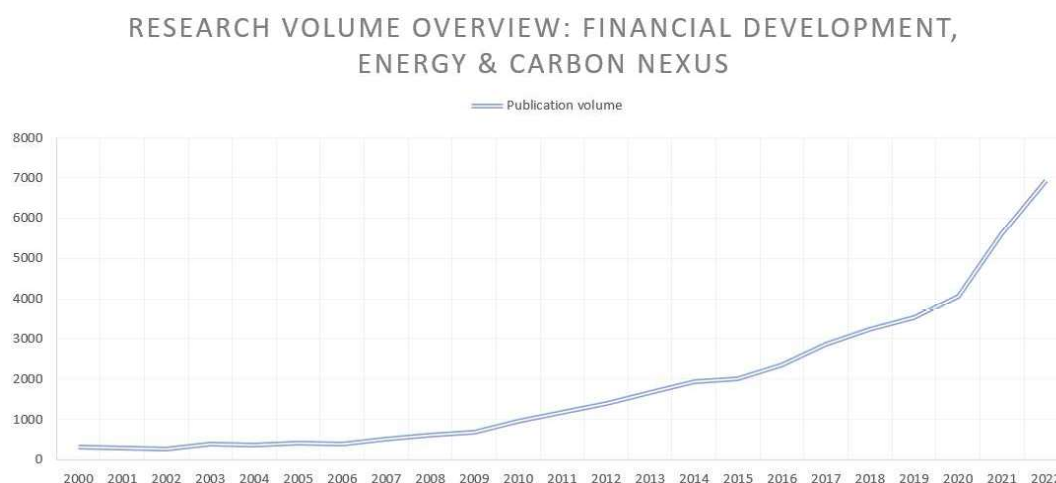


FIGURE 1 – Research Volume Overview : Financial development, Energy Carbon Nexus
Source : Data obtained from Science Direct.

The role of stock markets in addressing environmental concerns is now front and center. As major drivers of economic activity, stock markets have the potential to impact significantly on environmental dynamics. Recognizing this potential link is essential to achieving environmental goals. Growing sustainability awareness has led to an emphasis on responsible investment, where investors favor companies with environmentally friendly practices. As a result, stock markets have become critical drivers for companies to adopt greener practices to increase their market value and meet the growing demand for sustainable initiatives. In addition, the increase in environmental, social, and governance (ESG) criteria in investment decisions, as depicted in Figure 2, illustrates the interaction between financial markets and environmental factors. Stock markets, by facilitating investment in environmentally friendly companies and influencing corporate behavior, are increasingly seen as potential catalysts for environmental progress.

The role of energy markets in environmental sustainability is fundamental. Energy management and structure have a significant impact on the global ecological footprint. In this context, the transformation of the oil market has been particularly remarkable. Modern oil prices encompass not only the traditional interplay of supply and demand but also reflect economic activities more widely. As Kilian (2009) has shown, oil price fluctuations are linked to supply constraints and changing demand, highlighting their complex relationship with economic performance.

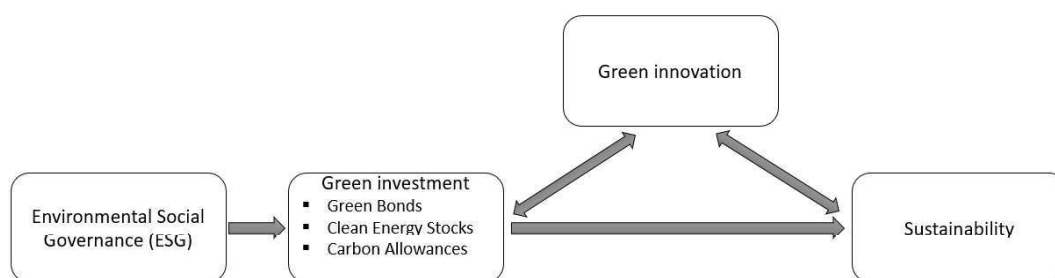


FIGURE 2 – ESG-Driven Investment in Green Finance for Sustainable Futures

This complex relationship underlines the need to address energy consumption patterns to ensure environmental and economic stability. In addition, developing renewable energy sources is a key route to advancing sustainable energy practices. The shift from fossil fuels to renewable energy sources could reduce carbon emissions and mitigate the adverse effects of energy-intensive practices, ensuring a more harmonious coexistence between economic growth and environmental preservation.

Carbon emissions and carbon markets play a central role in today's sustainable development landscape. Carbon emissions from human activities and industries have significant environmental implications, contributing to global warming and climate change. In response to this challenge, carbon markets have emerged as innovative mechanisms for reducing emissions. By establishing a financial value for carbon emissions, these markets encourage industries to reduce their carbon footprint and adopt cleaner practices. This dual interaction between carbon emissions and carbon markets reflects a dynamic effort to balance economic growth and environmental preservation. Figure 3 illustrates a significant trend indicating the commitment level among large corporations towards achieving carbon neutrality or net zero emissions. The voluntary carbon market has grown substantially for three consecutive years, resulting in a remarkable increase in emissions and demand for carbon credits. This increase is primarily attributed to the growing prevalence and strengthening of corporate net-zero commitments and other climate-related obligations. Notably, the number of companies committing to net zero emissions by 2022 has multiplied by four compared to 2015 figures.

Nowadays, academics and policy-makers are increasingly integrating environmental considerations into the framework of a sustainable economy and finance. Recognizing the vital link between environmental quality and human activities, it is acknowledged that environmental performance is essential to our well-being and economic progress. In economics and finance, some experts suggest governments should prioritize cleaner energy, regulate trade openness, and optimize industrial structure to improve environmental performance (Managi and Kumar, 2009; Press, 2007).

Accordingly, in pursuit of sustainable development goals, it becomes imperative to address and manage carbon dioxide (CO₂) emissions. This requires formulating well-thought-out policy measures that recognize the urgency of

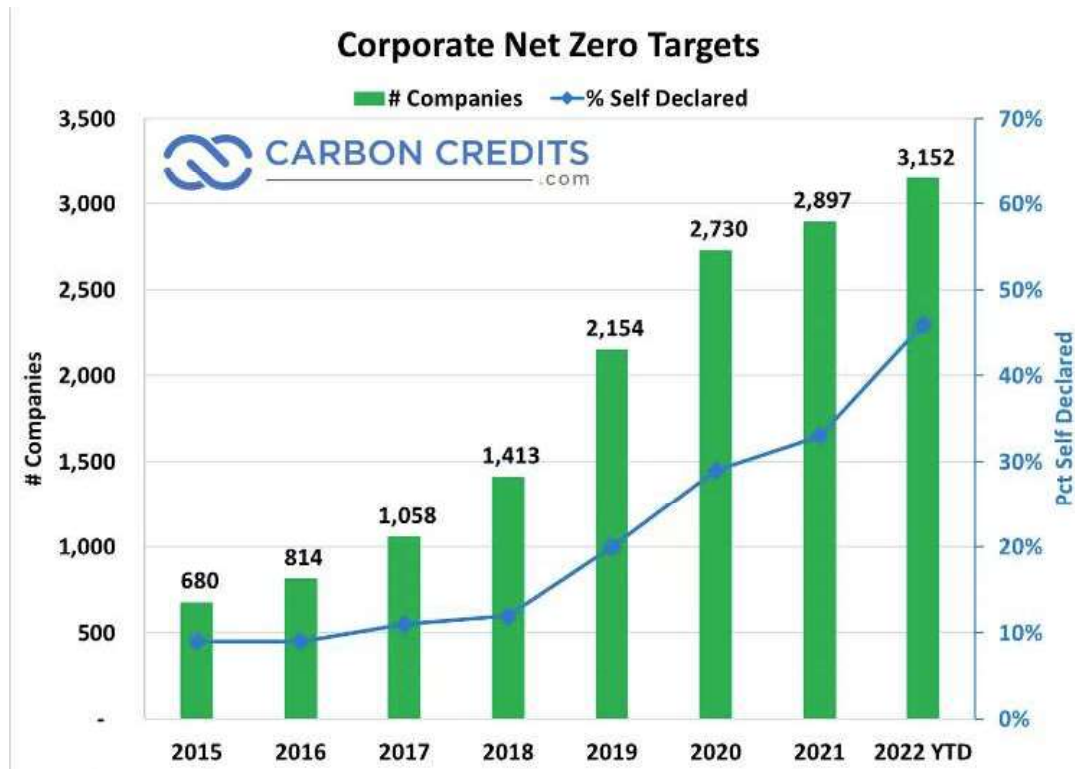


FIGURE 3 – Corporate Commitment to Carbon Neutrality and Net Zero Emissions
Source : MSCI

reducing CO₂ emissions. However, developing effective strategies to control CO₂ emissions relies on a comprehensive analysis of the underlying factors that contribute to them. In this sense, researchers have been actively engaged in recent years in examining the determinants of greenhouse gas (GHG) emissions, with a particular focus on CO₂ emissions. Their research has identified various economic, social, and political factors.

RESEARCH VOLUME OVERVIEW: STOCK MARKET, ENERGY & CARBON NEXUS

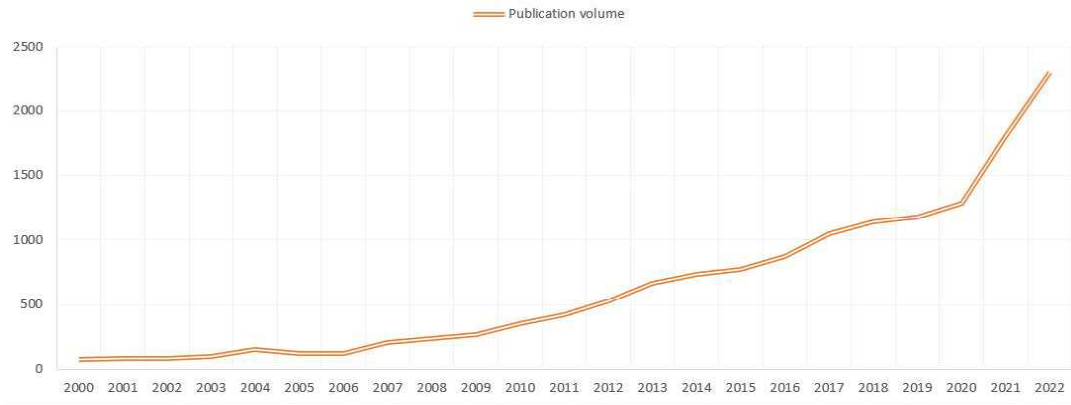


FIGURE 4 – Research Volume Overview : Stock Market, Energy Carbon Nexus
Source : Data obtained from Science Direct.

This thesis fills a gap in the existing literature by investigating the link between finance, energy, and the environment. It explores the role of financial instruments in ensuring environmental integrity. This exploration is conducted through four comprehensive research studies, each focusing on a distinct aspect of this relationships. As a result, these research studies collectively provide insight into various factors and markets that influence environmental conditions. The contribution of these studies is numerous. They enhance our understanding of the interaction between financial development and vulnerability to climate change. Additionally, the findings of these research studies offer a broader perspective on the complex link between financial development and environmental degradation. These insights contribute to the literature and lay the foundations for future researchers to replicate and develop this study. This potential replication offers the opportunity to address our current urgent environmental challenges. The introductory chapter begins by presenting an overview of key ideas, highlighting areas of research that need further exploration, introducing the research question, and outlining the structure of the thesis. The following chapters (2, 3, 4, and 5) are devoted to these four research studies on the interaction between finance, energy, and carbon. Table 1 summarizes these research studies. The research concludes with an in-depth discussion of the main findings and their wider implications.

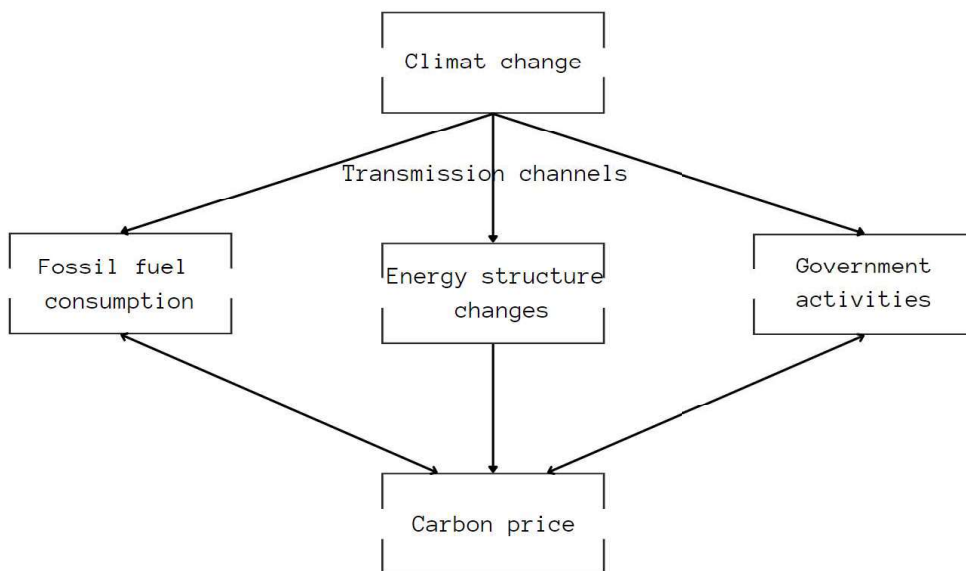


FIGURE 5 – Transmission Channels from Climate Change to Carbon Pricing

Research Study Title	Methodology Used	Key Contributions	Status of the Paper
<i>On the Asymmetric Relationship between Stock Market Development, Energy Efficiency, and Environmental Quality : A Nonlinear Analysis</i>	Linear and non-linear panel ARDL models	The study explores the dynamic non-linear relationship between stock market development, energy efficiency, and carbon emissions in emerging market economies.	Published
<i>Asymmetric Connectedness among Stocks, Energy, and Carbon Emissions Trading Systems in Europe and China</i>	VAR-asymmetric BEKK-GARCH model and DCC-GARCH model	This study examines the spillover effects between stock market indices, oil price, green bond, and carbon market returns in Europe and China. It provides insight into the interdependence of these markets.	Under Revision
<i>Asymmetric Effects of Decomposed Oil-Price Shocks on Carbon Markets : Comparative Analysis</i>	TVP-SVAR-SV model	This study analyzes the effects of oil supply, demand, and risk shocks on carbon markets in Europe and China. It explores how the carbon market responds to economic activities and risks in different contexts and regulatory conditions.	Submitted
<i>The Interconnectedness of Carbon, Fossil Fuels, and Renewable Markets in the Context of Climate Change</i>	TVP-VAR, DCC-GARCH models combined with Diebold and Yilmaz's (2012) connectedness network	The study explores the complex interconnectedness of major fossil fuel markets, global clean energy indices, and carbon markets in Europe and China. It explores how these markets are interconnected and influence each other.	Submitted

TABLE 1 – Thesis Research Studies Overview

Chapitre 1

The Environment-Energy-Finance Nexus

Climate change is emerging as one of the most critical and crucial challenges of the 21st century, casting a pervasive and ominous shadow over ecological, economic and social systems. Its far-reaching effects extend to the well-being of every individual, underscoring the urgency of dealing with its complex implications. The last decade has seen a remarkable expansion in the scale and importance of strategies to adapt to climate change. These strategies, championed by government bodies operating at local, regional, and global levels, seek to mitigate the far-reaching ecological, economic, and social consequences of climate change. The European Union's "A Clean Planet for All" initiative, a key component of Europe's "Green Deal" with its vision of decarbonizing the economy and promoting ecological vitality (European Commission, 2018), exemplifies these efforts. As attention shifts to climate adaptation and mitigation strategies, exploration of the equitable dimensions and complex role of the financial sector in this multi-dimensional network intensifies.

In this context, emerging economies and low-income countries find themselves in a paradoxical situation. While contributing less proportionately to the root cause of the problem, these nations bear a disproportionately heavier burden due to the negative externalities resulting from climate change (IPCC 2022). Although developed countries historically account for most greenhouse gas (GHG) emissions and per capita emissions, achieving climate stabilization goals requires emissions reductions from emerging economies. Moreover, these economies are particularly vulnerable to the impacts of climate change, which are further exacerbated by heightened vulnerabilities arising from intense pressures on local and regional ecological systems (Gilding, 2011). This vulnerability is compounded by the structural constraints faced by emerging economies and low-income countries, particularly in terms of economic and financial capacity. These constraints hamper their ability to effectively formulate and implement climate change mitigation and adaptation strategies (Dafermos, Nikolaidi 2019).

Although seemingly minor, these aspects are of considerable importance in determining the efficient use and risks associated with the financial assets that developing nations can commit, as the development finance literature demonstrates (Raj 1998; Cohen et al. 2008). Dimensions involving exogenous capital resources and complex fi-

nancial relationships between countries have long been controversial issues in development economics and finance (Raj 1998 ; Kregel 2004), as well as in more structurally oriented post-Keynesian macroeconomics (Bonizzi 2017).

The core of this thesis is a comprehensive exploration of the complex links between finance, energy, carbon emissions, and the carbon market. This complex interplay is key to addressing the immediate and long-term global challenges we face. As financial systems, energy markets, and especially carbon market become increasingly intertwined, it becomes essential to decipher their dynamics for addressing global challenges and achieving environmental sustainability. However, unravelling the operational context of these markets requires a fundamental understanding of the origins, underpinnings, and anticipated consequences of climate change. The close links between finance, energy, carbon emissions, and the carbon market underline the need for in-depth research into the multifaceted interactions and potential impacts. Financial decisions and energy consumption patterns exert a significant influence on carbon prices, while environmental policies and changes can reshape energy markets, affect carbon emissions, and impact financial performance. Thus, this first chapter of the thesis not only serves as an introduction, but also lays the foundations for an in-depth study of these complex relationships. The insights gained have far-reaching implications for policy formulation, investment strategies, carbon reduction initiatives, and the overall pursuit of environmental sustainability in our ever-changing world.

1.1 Contextualizing the Environment-Economic-Finance Nexus

1.1.1 Exploring Climate Change

The context of Climate Change

In recent times, concentrations of greenhouse gases in the Earth's atmosphere have been rising rapidly, particularly carbon dioxide. This rise in carbon dioxide levels is mainly due to the burning of coal, oil, and natural gas, commonly known as "fossil fuels". On a global scale, these fossil fuels have become a convenient source of energy for transport and power generation, as well as serving as a vital source of heat for homes and industrial processes. Widespread deforestation has also contributed to atmospheric change. In other words, as trees mature, they absorb carbon dioxide, then release greenhouse gases when they are felled and then burnt or left to decay.

Today, carbon dioxide levels are almost one and a half times higher than they were during the Industrial Revolution, some two centuries ago. As carbon dioxide levels rise, the planet experiences increased heat retention, resulting in a rise in the earth's temperature. This phenomenon, known as "global warming", leads to a general increase in temperatures on land surfaces and in the oceans.

The debate on measures to combat climate change invariably focuses on the critical role of carbon emissions in global warming and the consequences that flow from it. Carbon emissions, mainly in the form of carbon dioxide (CO₂) released into the atmosphere by human activities such as fossil fuel combustion, deforestation, and industrial

processes, have become the focus of efforts to mitigate climate change. The accumulation of these emissions leads to a greenhouse effect, meaning that certain gases trap heat in the atmosphere, resulting in an overall rise in global temperatures. Consequently, understanding, quantifying, and effectively managing carbon emissions have become essential aspects of climate change mitigation strategies.

One of the main measures of carbon emissions is the concentration of CO₂ in the atmosphere. This measure is tracked over time using data collected from a variety of sources, including monitoring stations, satellites, and ice cores. The continuous upward trend in atmospheric CO₂ concentrations since the industrial revolution underlines the scale of human impact on the planet's climate system. The Keeling curve, which graphically represents this rise in atmospheric CO₂ levels, is a stark reminder of the urgent need to reduce carbon emissions.

Mitigating carbon emissions involves efforts to reduce emissions at source and strengthen the carbon sinks that can absorb CO₂ from the atmosphere. This means moving away from fossil fuel-based energy systems to cleaner, renewable alternatives such as solar, wind, and hydroelectric power. The adoption of energy-efficient technologies, sustainable practices, and afforestation programs also contributes to reducing carbon emissions. Various international agreements, such as the Paris Agreement, have underlined the importance of countries setting and meeting targets to limit carbon emissions, thus fostering a global commitment to combat climate change.

Carbon emissions are intrinsically linked to the broader issue of sustainable development. Balancing economic growth and emissions reduction is a complex challenge, particularly for developing economies heavily dependent on fossil fuels. Policy measures, technological innovations, and financial incentives can play a key role in facilitating this transition. In addition, measuring carbon emissions provides a tangible indicator for assessing the effectiveness of climate policies and tracking progress toward emission reduction targets. In essence, measuring and managing carbon emissions is the essential key to the international response to climate change, indicating a collective determination to mitigate its most significant drivers and ensure a sustainable future.

Impact of Climate Change on Economies and Societies

Climate change and environmental degradation exert a significant influence on the state of a sustainable economy, impacting both financial and non-financial institutions (Sullivan 2014 ; Ozili, 2020). The potential negative effects of climate change on economic activities become evident through climate risks, which have adverse consequences for human well-being and future livelihoods. Effectively managing these climate risks and addressing the resulting loss and damage requires societal decision-making, proactive management, and the ability to forecast future greenhouse gas emissions and their implications for socio-economic development and equity. Figure 1 illustrates the relationship between emissions scenarios and future warming, highlighting the profound impact of climate change on the lives of different generations (those born in 1950, 1980, and 2020). This presentation underlines the transformative potential of climate change and its imminent ability to change the course of life. It also underlines the pressing responsibility that individuals now have to move away from today's greenhouse gas emissions and guide

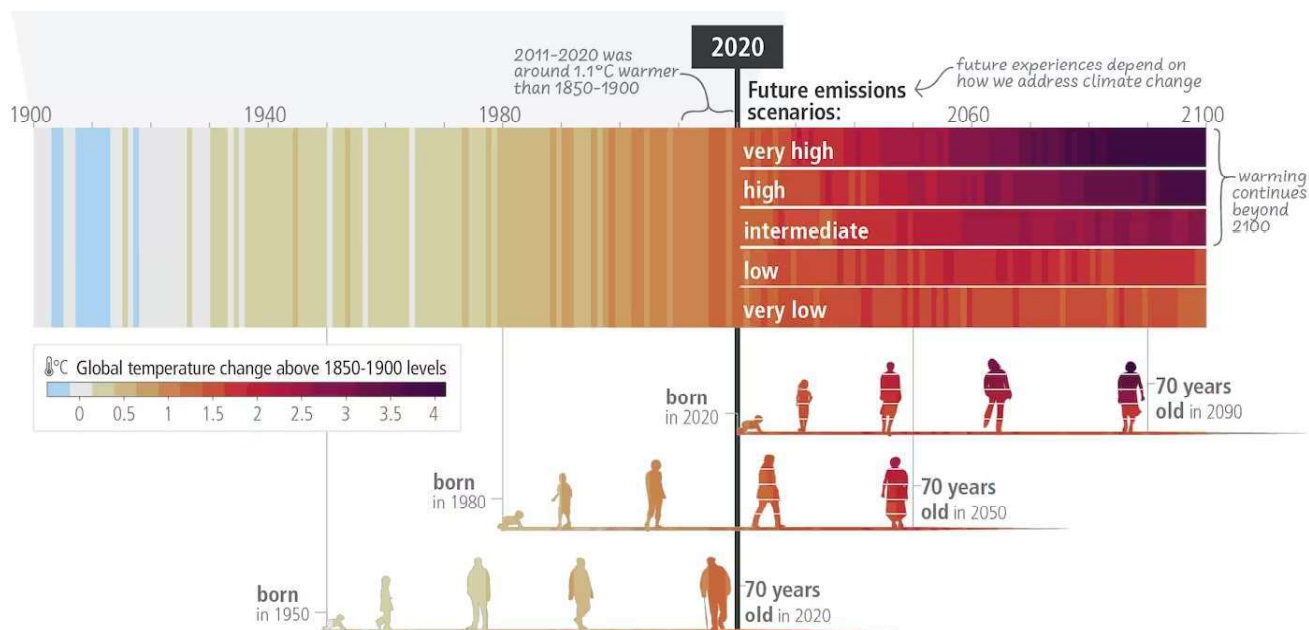


FIGURE 1.1 – Climate Choices : Shaping Our Future for Generations Ahead
 Source : Intergovernmental Panel on Climate Change 2020

the course of the coming decades toward a sustainable and resilient future.

Human activity is a major contributor to climate change and one of the world's most pressing challenges. The concentration of carbon dioxide in the atmosphere continues to rise each year. While energy remains a fundamental driver of economic progress, meeting changing demand at different stages of economic development requires sustainable solutions to environmental problems. Existing literature highlights various approaches and hypotheses concerning the interaction between economic growth and environmental pollution. On the one hand, research reveals that environmental quality is influenced by levels of per capita income, leading to changes in environmental policies and lending credibility to the idea that higher per capita income correlates with greater environmental degradation. On the other hand, it is postulated that the ability to manage climate-related stress depends on levels of economic growth and is strongly influenced by the health of the financial sector, well-structured institutions, robust health systems, and levels of education.

During the preceding thirty years, a majority of developed countries and several developing economies have been actively engaged in implementing policies to combat environmental degradation. In this respect, the Organisation for Economic Co-operation and Development (OECD) has played an important role, regularly contributing to discussions and initiatives on effective climate change policies. The organization has also demonstrated its effectiveness in assessing the performance of these policies in different countries. The Intergovernmental Panel on Climate Change (IPCC) has also presented estimates suggesting that the adoption of economically efficient market-based approaches, such as carbon pricing and emissions trading, could lead to relatively inexpensive reductions in CO₂ emissions. This approach could make an overall contribution to global mitigation efforts (OECD, 2007). However,

while the initial costs of these measures may increase, the choice of less effective alternatives, such as prioritizing administrative or regulatory instruments or exempting energy-intensive activities from taxation or trading schemes, could prove more costly in the long term.

To reduce the proportion of CO₂ emissions, it is necessary to significantly alter the scale and composition of fossil fuel use in order to reduce the carbon content associated with fuel production and consumption. One approach is to introduce a carbon tax on fossil fuels, determined according to the carbon content of the fuel. Pearce (1991) reviewed recent literature examining the potential outcomes of carbon taxes. Barker and Lewney (1991) have lately made notable contributions to the macroeconomic modeling of environmental policies, while Sondheimer (1991) has particularly explored the macroeconomic implications of carbon taxes. Boero, Clarke and Winters (1996) provided a comprehensive review of the long-term macroeconomic implications of reducing greenhouse gas emissions. However, none of these studies considered the effects of a carbon tax on the prices of non-fuel domestic goods, despite the fact that a significant proportion of CO₂ emissions come from the production of goods in industrial activities.

Many policy measures can be used to establish a pricing mechanism for CO₂ emissions, including carbon or energy taxes, the removal of environmentally harmful subsidies, tradable permit systems, and the project-based flexibility mechanisms described in the Kyoto Protocol to the United Nations Framework Convention on Environmental Quality (OECD, 2007). While most OECD countries have implemented one or more of these measures to varying degrees, the main challenge is to expand their adoption and link them together to create a consistent and robust price signal for all activities generating CO₂ emissions. The introduction of an international carbon price not only reduces the overall costs associated with CO₂ emissions but also helps to level the playing field between nations, addressing concerns about the potential impacts on the effectiveness of environmental conservation policies. While a number of OECD countries have instituted energy taxes to some extent, only a handful have imposed carbon taxes. This fiscal approach to reducing CO₂ emissions can be highly cost-effective. Nevertheless, the effectiveness of these measures within the OECD has often been reduced by the granting of energy tax rebates or exemptions, mainly targeting.

1.1.2 Scientific Insight and Economic and Financial Risks of Climate Change

Scientific evidence

Since the mid-1800s, scientists have recognized the essential role of CO₂ as the main greenhouse gas affecting the Earth's energy balance. Empirical measurements of CO₂ levels in the atmosphere, including data extracted from ice cores, demonstrate a staggering 40% increase in atmospheric CO₂ concentration between 1800 and 2019. Examination of various forms of carbon, such as isotope analysis, unequivocally attributes this increase to human activities. In addition, human activities also contribute to rising levels of other greenhouse gases, notably methane and nitrous oxide. The perceptible rise in global surface temperatures since 1900 perfectly aligns with the

meticulous calculations assessing the impact of increasing greenhouse gases in the atmosphere, combined with other human-made alterations, on the Earth's energy balance.

Scientists believe that anticipated climate change is due to how greenhouse gases retain heat. The fundamental understanding of greenhouse gas physics and the distinctive patterns uncovered in the fingerprint studies agree that natural factors alone are insufficient to elucidate recent climate change. These natural factors include variations in solar radiation, the Earth's orbital dynamics, volcanic events, and intrinsic climate fluctuations such as El Niño and La Niña ¹. Sophisticated computer models, configured to simulate global temperature trends solely due to these natural factors (Houghton, 2004), predict minimal surface warming or even marginal cooling over the 20th and 21st centuries. However, observed temperature changes align with climate models that consider human-induced changes in atmospheric composition.

In 2019, the concentration of CO₂ in the earth's atmosphere exceeded levels observed in the 19th century by 40%. Most of this increase has occurred since around 1970, coinciding with a sharp rise in global energy consumption. Scientific measurements have shown a decrease in the proportions of other carbon isotopes, namely ¹⁴C and ¹³C, and a slight reduction in oxygen concentration in the atmosphere, first observed in 1990. These indicators clearly show that the primary source of the increase in CO₂ is the combustion of fossil fuels, characterized by low ratios of ¹³C and an absence of ¹⁴C. In addition, carbon emissions from deforestation and changes in land use have contributed to the release of carbon from the biosphere, where it naturally resides for long periods, usually decades or centuries. The additional CO₂ from fossil fuel combustion and deforestation has upset the delicate balance of the carbon cycle. Unfortunately, the natural processes capable of restoring this balance operate much slower than the rapid rates at which human activities infuse CO₂ into the atmosphere.

Therefore, a significant proportion of the CO₂ generated by human activities remains in the atmosphere, and some of this CO₂ persists not just for decades or centuries but for thousands of years. Compared with CO₂ levels measured in ice cores, current atmospheric concentrations are significantly higher than they have been for at least 800,000 years.

As a result, a significant proportion of the CO₂ generated by human activities remains in the atmosphere, and some of this CO₂ persists not just for decades or centuries but for thousands of years, as confirmed by the National Academy of Sciences (NAS). Compared with CO₂ levels measured in ice cores, current atmospheric concentrations are significantly higher than they have been for at least 800,000 years.

As the persistence of CO₂ in the atmosphere unfolds over vast time scales, the ensuing exploration will focus on the economic and financial risks intimately linked to these environmental changes, revealing the interconnectedness of the challenges posed by climate change.

1. El Niño and La Niña are two phases of a natural climate phenomenon known as the El Niño-Southern Oscillation (ENSO). El Niño corresponds to warming sea surface temperatures in the Pacific Ocean, which disrupts global weather patterns. At the same time, La Niña is characterized by cooler sea surface temperatures and has contrasting effects on weather conditions. These phenomena significantly impact a global scale, influencing precipitation, temperatures, and extreme weather events in various regions. Scientists monitor ENSO to predict and respond to climate-related changes.

Economic and financial risks

Since its creation in 1988, the Intergovernmental Panel on Climate Change (IPCC) has played a vital role in improving our understanding of the reality, scope, and underlying causes of climate change. This awareness has gradually spread to a broader segment of society and even to economic decision-makers. However, despite the gradual recognition of the anthropogenic origins of climate change by political decision-makers and business leaders worldwide, the financial sector remained curiously absent from this discourse for an extended period. Remarkably, this landscape has undergone a rapid transformation in recent years. In a relatively short time, finance has emerged as a critical player in the economic dialogue on climate change, aligning itself with the main greenhouse gas (GHG) emitting sectors, notably fossil fuels. The following text provides an overview of this concise history, focusing on the financial sector's exposure to the risks posed by climate change.

For a long time, the financial sector primarily perceived climate change as an external disruption, something analogous to a series of ordinary weather disturbances occurring daily worldwide. It was commonly regarded as a problem that, if it ever became a concern, would potentially fall within the scope of operational risk frameworks, and then only if there were severe consequences on the horizon of several decades. For the financial sector, climate change was not seen as an urgent problem but rather as a long-term issue to be addressed by political decision-makers. In the early 2000s, a few pioneering financial institutions began to take an interest in climate change, but through the prism of their project finance activities. Their approach mainly assessed social and environmental risks, focusing on project-related risks and their environmental impact. This initial perspective could be characterized as a form of climate change denial. One of the primary motivations for these pioneers was the growing pressure exerted by environmental non-governmental organizations (NGOs) on highly polluting energy projects. Their efforts were motivated by a desire to manage the reputational risks associated with these projects.

The next step in this evolution was the emergence of carbon markets, driven by the Kyoto Protocol. In 2005, this international agreement paved the way for the European Union Emissions Trading Scheme (EU-ETS), a mechanism designed to allocate carbon allowances to companies for compliance purposes. Some financial institutions, particularly investment banks, have recognized the potential of carbon markets as a new avenue for business development. They have closely integrated carbon market activities with their energy trading desks, enhancing their understanding of climate change and associated mitigation policies.

The emergence of socially responsible investment (SRI) in the early 2000s catalyzed raising investor awareness of climate change. Initially championed by charitable funds, this awareness spread to pension funds and SRI-focused asset managers. The underlying motivation for this shift was twofold. Firstly, it was rooted in ethical considerations, reflecting a moral imperative to combat climate change. Secondly, and more importantly, it stemmed from a risk management perspective that, in principle, transcended the boundaries of SRI. This perspective sees climate change as a potential source of financial risk, likely to impact investment returns. In addition, it also

recognized the anticipated risk associated with a policy-induced increase in carbon pricing.

Following the framework of Carney (2016), it is essential to highlight the multifaceted impact of climate change on investors, which encompasses three distinct channels : physical risk, liability risk, and transition risk.

As the first channel, physical risk is about the tangible impacts of assets and property from increasingly severe climate risks, including storms, wildfires, hurricanes, floods, and droughts (Carney, 2016). The tangible effects of climate change are already evident in global investment plans, with extreme climate-related events such as hurricanes and droughts introducing increased uncertainty for businesses and financial markets (Rose-Smith, 2015 ; Subramaniam, 2016). Without rapid mitigation measures, climate change is poised to reshape the global economic landscape by amplifying financial vulnerabilities and intensifying economic and human losses (Ricke et al., 2018). Projections point to an increase in the frequency of severe weather events due to global warming (Forzieri et al., 2018), which, in turn, is likely to lead to an increase in the physical and financial damage resulting from these events.

Dealing with these losses has multiple implications. When losses are covered by insurance, they directly impact the insurance and reinsurance sector, which can lead to portfolio losses for insurance companies. When losses are not insured, the responsibility for repairing damaged property falls on the owners or the government. For example, the financial cost of hurricanes in the United States in 2017 was estimated at between \$65 billion and \$190 billion (Irfan, 2017). According to Forzieri et al. (2018), the impact of climate-related events is set to increase threefold by the 2020s and sixfold by mid-century, mainly affecting sectors such as industry, transport, and energy. Recent studies suggest that even with a complete elimination of greenhouse gas emissions, it remains unlikely that the 2°Celsius target will be reached. Consequently, the global economy remains sensitive to climate-related physical events' impacts, as Raftery et al. (2017) indicated.

Furthermore, liability risks arise as affected parties seek compensation for losses attributed to escalating climate change impacts. The growing body of climate science is expected to strengthen climate-related legislation, as Marjanac and Patton (2018) point out. This proliferation of climate-related legislation at different levels of governance is leading to an increase in legal action against carbon-intensive companies (Bloomberg, 2018). Individuals, NGOs, and civil society organizations affected by climate change can seek financial compensation from those deemed responsible for their losses. As extreme climate impacts persist, these claims will likely increase in frequency over the medium to long term. Many non-governmental organizations are actively supporting these global awareness-raising efforts. An outcome arising from these liability risks could trigger a significant shift in consumer preferences, as suggested by Schoenmaker and Schramade (2019). This shift, driven by changes in household consumption patterns and supported by the intensification of advertising campaigns promoting responsible investment, represents a substantial risk that could impact corporate business models.

Transition risk involves the potential transformation of a successful business into a precarious one due to abrupt changes in policy or technology. This risk is the consequence of rapid political and technological changes made necessary by the imperative to transition to a resilient, low-carbon economy. For example, introducing climate-

friendly policies to accelerate the adoption of renewable energy sources can significantly impact the valuation of financial assets associated with carbon-intensive industries (Mercer, 2015; Battiston et al., 2017). It is essential to underline that these risks are not simple incidents but interconnected, complex, non-linear, and dynamically changing. In addition, climate change policies, as Guyatt (2011) highlights, represent the most critical risk factors for investors. In addition, investors may suffer losses resulting from the indirect consequences of climate change. According to Cahen-Fourot et al. (2021), all fossil fuel-related capital and industrial facilities that rely on fossil fuels will likely suffer the consequences of a rapid transition to a low-carbon economy. As a result, climate change is likely to undermine economic growth and induce political instability, which could lead to lower investment returns (De Nederlandsche Bank, 2017).

In the area of finance, these risks are referred to as "transition risks". These risks represent the financial risks associated with transforming the energy and industrial sectors in the context of climate change mitigation. These transition risks have multiple aspects and come from a variety of sources, classified into political and legal risks, technological risks, market risks, and reputational risks, as defined by the Task Force on Climate-related Financial Disclosures (TCFD, 2017).

1.1.3 Financial Markets and Equities : Tools for Climate Resilience and Sustainability

Concept of Sustainability

The concept of sustainability is a multi-dimensional concept subject to diverse interpretations, often influenced by factors such as cultural backgrounds, affiliations with multinational corporations, ownership of small businesses, or individual efforts to define a sustainable lifestyle (McNall et al., 2011). However, precisely defining this concept is far from easy due to its diverse and sometimes contradictory meanings. According to Agyekum Mensah et al. (2012), sustainability as a concept has relatively recent origins, dating back to a conference held in the 1970s. Similarly, Kamara et al. (2006) assert that the notion of sustainability emerged from the United Nations Conference on the Human Environment (UNEP, 1972). The most widely accepted definition of sustainable development, summarized in the 1987 Brundtland Report, describes it as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs".

By adopting this definition, a deeper understanding of the concept of sustainability emerges, revealing its inherent complexity. Drawing primarily on the Brundtland Report, the temporal dimension takes center stage, encompassing the immediate and distant future. Recognition of an intertemporal perspective is inherent to sustainable development, as it considers the complex interconnection between current actions and their potential repercussions over long periods of time.

This concept of sustainability reflects the complex interconnections between human activity and environmental well-being. As this chapter examines the link between the environment, energy, and finance, it is essential to reco-

grize that sustainability underlines the responsibility of developing this complex network. The multiple interpretations of sustainability remind us that it is not simply an abstract concept but a lens through which we see the complexities of our choices, our systems, and the intricate balance between current prosperity and future well-being.

Renneboog et al. (2011) further reveal that SRI funds, when taking risk-adjusted abnormal returns into account, show an average annual reduction in returns of around 2% compared to comparable conventional funds. This suggests that the selection criteria used in SRI introduce constraints that generally lead to lower returns. However, an exception to this trend is observed in the social category, where results are somewhat mixed. Furthermore, engagement in activism and internal SRI research will likely improve returns. These results support the argument that the selection process generates value-relevant information in some cases.

Concept of Resilience

The concept of resilience has evolved dynamically, like a moving target in constant redefinition. Initially existing in systems theory, resilience was narrowly defined as the ability of a system to bounce back or return to equilibrium after a disturbance, often referred to as "technical resilience" (Holling, 1973). However, it has since evolved into a more complex concept, with resilience in complex adaptive systems going beyond simple resistance to change and preservation of existing structures (Folke, 2006). This evolved perspective encompasses multiple dimensions : (i) A system's ability to adapt to change while retaining its function and structure ; (ii) Degree of system self-organization ; (iii) The ability to enhance learning, adaptation, and, when necessary, transformation (Berkes et al., 2003). In this conceptualization, adaptability implies the ability of a system or its components to learn, integrate knowledge and experience, adjust responses to changing external and internal factors, and continue to develop within the current domain of stability (Berkes et al., 2003). Conversely, transformability implies the creation of a fundamentally new system when existing ecological, economic or social structures are no longer viable (Walker et al., 2004).

In addition to the notion of absorptive or persistence capacity, which encompasses various strategies employed by individuals or households to mitigate the impact of shocks on their livelihoods and basic needs, three fundamental dimensions are considered to be essential aspects of resilience : absorptive capacity, adaptive capacity and transformative capacity (Walker et al., 2004 ; Folke, 2006 ; Folke et al., 2010 ; Miller et al., 2010). This three-dimensional conceptualization is intriguing because it emphasizes that resilience is not the result of a single capacity but rather an interaction between the three.

Moreover, these different responses can be related to different shock intensities, with the effectiveness of resistance strategies closely linked to the intensity of the initial shock. When the intensity of the initial shock is relatively low, systems are more likely to resist it effectively, absorbing its effects with no discernible consequences for their function, status, or state. Norris et al. (2008) emphasize the ideal outcome of resilience after a crisis, asserting that resources effectively block the stressor, resulting in a near-total absence of dysfunction, whatever its temporary nature. This concept extends beyond individuals, as even large systems regularly employ resistance strategies. Fur-

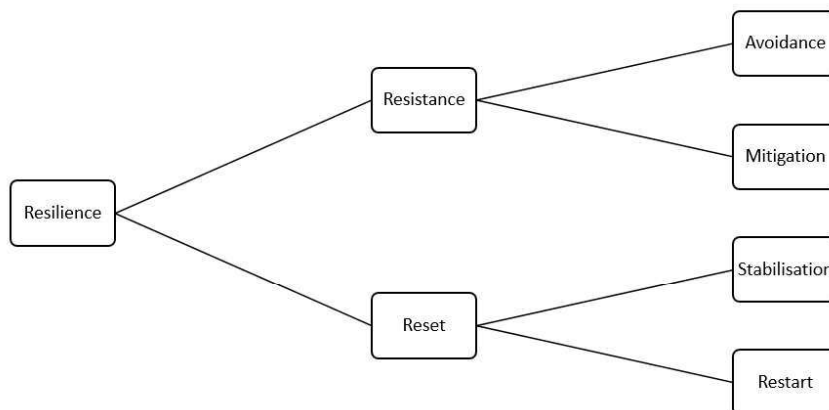


FIGURE 1.2 – Resilience in Management

Furthermore, resistance strategies are relevant on a larger scale for predictable risks, such as fire, which can be planned for and mitigated. In disaster risk management, many critical systems are deliberately designed to be resilient. For example, fire-resistant buildings and redundant power sources are designed to enable individuals, communities, or larger systems to resist disasters. When absorptive capacity reaches its limits, individuals must rely on their adaptive resilience, as proposed by Cutter et al. (2008). Adaptive resilience comprises a series of incremental adjustments to maintain functionality without undergoing significant qualitative changes in function or structural identity. These adaptive responses can be individual or collective and operate at different levels, from within the household to the community scale (Levine et al., 2011). Furthermore, adaptation appears to be a continuous and gradual process that can be difficult to track or measure. It often occurs without individuals or societies fully realizing how they adapt to changing circumstances (Levine et al., 2011 ; Hertel and Rosch, 2010).

Resilience is a vital consideration in financial markets, particularly in emerging markets. As Bryan Pascoe points out, "We need to accelerate the development of bond markets in many jurisdictions and regions, particularly in emerging markets". This acceleration is essential to strengthen the structural resilience and depth of emerging markets to meet their significant financing needs. While resilience bonds represent an encouraging first step, they still occupy a niche position. We need a broader range of economically and growth-oriented debt instruments to achieve greater resilience. Standardization of market instruments plays a key role in reducing barriers to investment, thus promoting a more resilient financial landscape. Recent research conducted between 1995 and 2017 reinforces the importance of climate resilience, showing that it positively impacts credit ratings in developing countries. Conversely, climate vulnerability negatively influences these ratings, highlighting the deep interconnection between financial resilience and environmental considerations (Cevik and Tovar Jalles, 2020).

Responsible Investment in Climate Solutions

Renneboog et al. (2011) study the behavior of ethical investors, particularly those who invest in socially responsible investment (SRI) funds. These investors prioritize the non-financial aspects of funds over past negative returns. The study investigates whether SRI fund inflows and outflows are influenced by past fund performance and compares this behavior with that of other fund types. The data set includes 410 SRI equity funds worldwide between 1992 and 2003. The results reveal that investments in SRI funds are less sensitive to negative past performance than investments in other fund types. In addition, these reactions vary geographically and differ according to the SRI category, including anti-loss, ethical, social, and environmental funds. This heterogeneity indicates that investor preferences vary in these areas. Environmental SRI fund flows notably show greater sensitivity to positive past returns, while other categories show lower sensitivities. Furthermore, the study confirms that substantial inflows do not correspond to higher subsequent returns, in line with the efficient market hypothesis.

Green bond : A financial asset with significant environmental impacts

One way of implementing climate-responsible investment is to allocate funds to green bonds. The class of financial instruments known as green bonds was introduced in 2007/2008 thanks to a collaboration between the Swedish bank Skandinaviska Enskilda Banken (SEB) and the World Bank. SEB envisaged green bonds to respond to the growing demand for environmentally oriented investments to encourage sustainable and resilient climate mitigation initiatives. Today, there is a whole range of green bonds, often called "climate bonds," whose main objective is to facilitate the financing of the transition to a low-carbon economy. What unites green or climate bonds is their inherent link to solutions to climate change, whether through emissions reductions, technological advances, renewable energy projects, or adaptation projects. The current market for green bond issuance has exploded, reaching \$33.03 billion in 2015, representing substantial growth from its value of \$3.9 billion in 2011 (Climate Bonds Initiative, 2015).

Green bonds are debt financing instruments for projects involving renewable energy, energy efficiency, low-carbon infrastructure, and sustainable resource use (see Figure 2). Investors in green bonds are mainly governments, international banks, pension funds, and large corporations. The Climate Bond Initiative website promotes green bonds by claiming that the favorable marketing signal generated by a green company outweighs the additional transaction costs associated with issuing green bonds. Indeed, academic research has affirmed that such signaling effects can produce positive returns on the stock market.

These bonds include a wide variety of options, such as green retail bonds (Holmes and Mabey, 2009), corporate green bonds (Helm, 2009), Green Investment Bank bonds (Green Investment Bank Commission, 2010), green gilts (Holmes, 2010), multilateral development bank green bonds (Veys, 2010), sectoral green bonds (IETA, 2010) and green infrastructure bonds (Caldecott, 2010). In particular, the concept of green bonds lacks specific criteria or



FIGURE 1.3 – Green bond investment mechanism

Source : ETEnergyWorld (Feb 16, 2021)

<https://energy.economictimes.indiatimes.com/news/renewable/opinion-green-bonding-for-recovery/80985453>

universally accepted definitions of what qualifies as "green". Some bonds call themselves green without external validation. To remedy this situation, a consortium of investors, issuers and underwriters adhering to the green bond principles has published voluntary guidelines for the green bond market (ICMA, 2015). These guidelines call for transparency and disclosure practices within the sector. In addition, Clapp et al. (2015) suggest that climate science should play a role in the independent verification of green bond environmental credentials. To improve the efficiency of the green bond market and advance our understanding of climate risk, clear and rigorous criteria should be established to determine whether a project qualifies as a green bond. It should be noted that there appears to be a gap in existing research on green bonds, particularly with regard to analyzing the performance of green bond portfolios.

Integrating Sustainable Finance into Economic Development

Sustainability is a multifaceted concept encompassing three dimensions : economic, environmental, and social, collectively known as the "triple bottom line" (Elkington, 1997 ; Magon et al., 2018). Figure 3 below illustrates the concept of sustainability and its three dimensions. The concept of the triple bottom line, first introduced by Elkington (1997), emerged in 1997 and emphasizes the inherent interconnectedness of corporate objectives with the societies and environments in which they operate. Economic sustainability concerns a company's ability to generate adequate financial resources, guaranteeing ongoing liquidity and sustainable long-term returns (Steurer and Konrad, 2009). Environmental sustainability is achieved when a company's consumption of natural resources remains below its replenishment rate while minimizing waste production and emissions (Vachon and Mao, 2008). Social sustainability is achieved by actively supporting the preservation and development of current and future generations' skills and capabilities, promoting health, and cultivating fair and democratic practices within and beyond the organization's boundaries (McKenzie, 2004).

The 2002 World Summit on Sustainable Development was a momentous occasion, bringing together a wide range of participants, including heads of state and government, national delegates, non-governmental organizations (NGOs) leaders, businesses, and other influential groups. The summit had one overriding objective : to focus the world's attention and mobilize collective efforts to address considerable challenges. These challenges centered on improving people's quality of life and preserving our planet's natural resources. It is essential to note that the world is faced with a pressing dilemma characterized by a growing population and increasing demand for necessities such as food, sanitation, water, energy, and economic stability (United Nations, 2002). Following the United Nations Conference on Sustainable Development in 2012, a momentous event that culminated in the adoption of the political declaration "The Future We Want", particular attention was paid to the practical steps to be taken to achieve sustainable development. The Rio conference brought together member states to deliberate on the launch of a collaborative effort. This effort was specifically aimed at developing a comprehensive set of Sustainable Development Goals (SDGs) that would not only build on the successes of the Millennium Development Goals but also align harmoniously with the broader post-2015 development agenda, as defined by the United Nations (2012).

Companies are increasingly seen as significant contributors to greenhouse gas emissions and environmental resource depletion, driving demand for environmentally friendly practices (Gadenne et al., 2009). Stakeholders and regulations have pushed for adopting environmentally friendly strategies, making corporate sustainability a leading area of research (Searcy and Buslovich, 2014). Corporate social responsibility (CSR) now encompasses environmental responsibility, reflecting its global recognition (Yadav et al., 2016). Corporate sustainability strategically aligns corporate productivity, value creation, and competitiveness with environmental, economic, and social dimensions (Kocmanova et al., 2011).

Researchers conducting event studies have found that environmentally friendly companies increase in value,

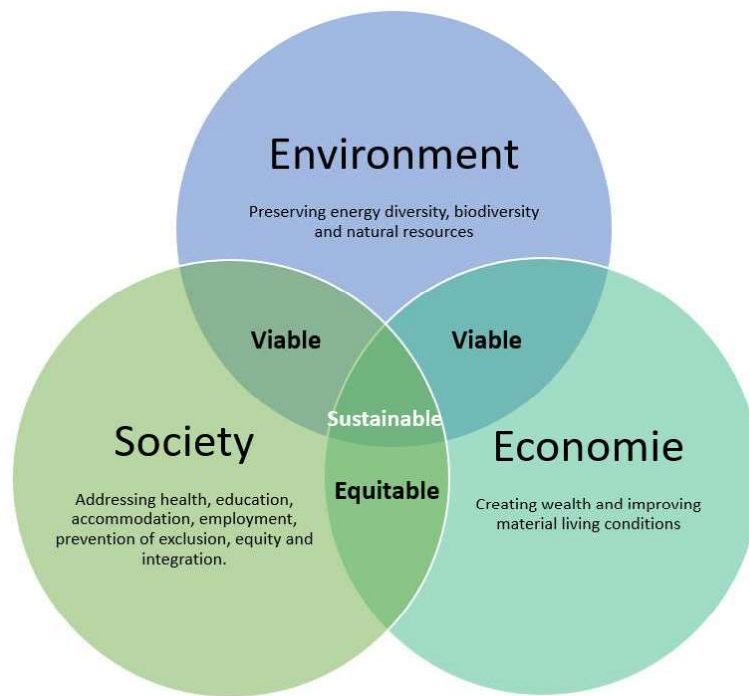


FIGURE 1.4 – Dimensions of Sustainability

while those associated with environmentally damaging events decrease in value (Flammer, 2013). Organizations integrate green initiatives into their strategies to mitigate environmental risks and potentially improve their financial performance, depending on their industry and environmental conditions. Against this backdrop, carbon markets have emerged as a significant solution for combating climate change and reducing carbon emissions.

Carbon Markets : A Market Solution to Climate Change

Emissions trading systems are mainly characterized by two distinct models : cap-and-trade systems and offset systems.

Cap-and-trade system : In a cap-and-trade system, a regulatory authority sets an overall cap or limit on the total amount of emissions that all participating entities can release over a given period. This cap is usually progressively reduced over time to meet emission reduction targets. Quotas or emission permits, each representing the right to emit a certain quantity of pollutants, are allocated to these entities. Entities that emit pollutants below their allocated quotas can sell their surplus quotas to those that exceed them. This creates a market for emissions trading, where the price of allowances is determined by supply and demand. The cap ensures that overall emissions remain within the desired limit, while the trading aspect allows flexibility in achieving reductions.

Baseline and credit system : In a baseline and credit system, also known as offset trading, entities receive credits for undertaking activities that reduce emissions beyond what is required by regulations. These credits can

then be sold to entities that need to offset their emissions. The baseline represents the level of emissions expected if no action were taken, and the credits represent the reduction achieved. This system encourages innovation and additional efforts to reduce emissions beyond regulatory requirements. However, it requires careful monitoring and verification to ensure that the emissions reductions announced are real and additional.

As illustrated in Figure 4, in a cap-and-trade system, an overall emissions limit is broken down into individual emissions permits, with each ETS permit representing one metric tonne of CO₂. These permits are acquired and traded between participants, according to the emissions resulting from their operational activities. If a participant exhausts its permits, it must either purchase additional permits from those holding a surplus or cease emissions.

Emissions trading schemes comprise three fundamental elements : (i) caps setting absolute limits on emissions : These caps set strict limits on the levels of emissions allowed for participating organizations ; (ii) the scarcity value of limited permits : The scarcity of permits under these caps gives them an intrinsic value, creating a market-determined cost for carbon emissions. This mechanism encourages participants to reduce their emissions by adopting more efficient operational practices or investing in low-carbon technologies ; (iii) permit trading for cost-effective reductions : Organizations can trade permits, facilitating emissions reductions in the most economically efficient way. This trading mechanism enables entities to optimize their emission reduction strategies.

The European Union Emissions Trading Scheme (EU ETS) is the most prominent international example of a cap-and-trade system, which has effectively paved the way for emissions reduction efforts on a continental scale. Moreover, the importance of emissions trading extends beyond Europe, with China emerging as a central player in this field. China's regional emissions trading initiatives, encompassing several provinces and cities, represent a crucial development in global efforts to combat climate change. As the world's largest emitter of greenhouse gases, China's commitment to emissions trading demonstrates its determination to manage the environment and can influence and shape global carbon markets.

Economic theory behind carbon markets

To stabilize carbon levels in the atmosphere and mitigate climate change, our efforts must not be limited to forest preservation, clean energy technologies, and emission reduction strategies. It is essential to stimulate market demand for these crucial solutions, and carbon markets are emerging as an innovative and economically efficient way of achieving these multiple objectives (Karmali, 2010). These markets not only create an attraction for forestry credits and emerging clean energy technologies but also introduce a tangible financial value for emissions, motivating individuals, companies, and governments to reduce their carbon footprint (Karmali, 2012).

Carbon markets, characterized by their dynamic and adaptive nature, are designed to efficiently allocate resources to the most cost-effective methods of reducing greenhouse gas (GHG) emissions. They operate on the principle of imposing penalties on entities that exceed predetermined emission limits while rewarding those that emit below these thresholds (Stern, 2006). This mechanism not only provides economic incentives to reduce emis-

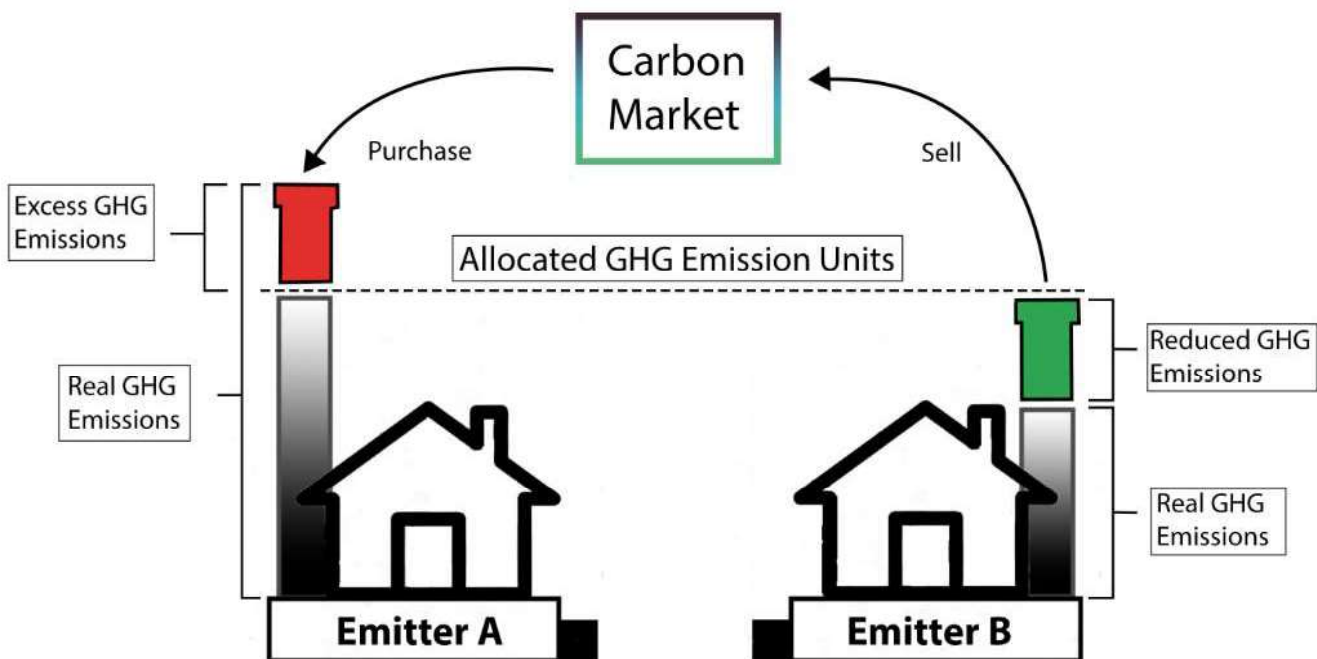


FIGURE 1.5 – The cap and trade system of carbon markets

sions but also encourages innovation in emission-reducing technologies and practices. By creating a market-based approach to emissions control, carbon markets ensure that emissions reductions are achieved in the most efficient and economically viable way.

Carbon markets are also distinguished by their inclusive nature. They invite third-party participants, including speculators and investors, to become involved in the process. These stakeholders play an essential role in facilitating investment in environmentally-friendly initiatives, accelerating the transition to a low-carbon economy. In addition, carbon markets encourage a wide range of stakeholders to get involved. Environmental organizations, for example, can play an active role in the market by seeking to reduce emissions below regulated targets. To do this, they can raise funds to buy and retire emission allowances, thereby increasing the cost of emissions and forcing emitters to improve their operational efficiency (Bayon et al., 2007).

EU Emissions Trading Scheme

The European Union Emissions Trading Scheme (EU ETS) is the world's largest carbon market initiative, covering a wide range of 10,000 installations. These include thermal power plants, coke ovens, mineral oil refineries, iron production and processing units, mining operations, and various glass, ceramics, paper, and pulp sectors. Launched in 2005, the European Emissions Trading Scheme operates as a cap-and-trade program, handling almost half of the European Union's carbon emissions (Soleille, 2006). To facilitate trading activities and ensure the smooth operation of the market, the European Climate Exchange (ECX) serves as the designated trading platform. ECX is crucial in improving market liquidity while offering participants benefits such as reduced transaction costs, minimized risk,

guaranteed anonymity, and price transparency (Labbat and White, 2008).

Chinese Emissions Trading Scheme

In its pursuit of sustainable environmental practices and as part of its commitment to tackling climate change, China has developed regional carbon markets. These regional initiatives, often called "pilot" carbon markets, represent an essential phase in China's broader strategy to regulate and reduce greenhouse gas emissions. Unlike its European counterpart, the European Union Emissions Trading Scheme (EU ETS), China's regional carbon markets use distinct mechanisms and approaches. Pilot carbon markets have played a key role in promoting low-carbon development in vital sectors such as energy, industry, construction, and transport. These initiatives have established best practices deemed worthy of replication and promotion. As these pilot markets matured, China embarked on a gradual journey toward developing its national carbon market, passing through three distinct stages of evolution : Preparation Phase, from 2013 to 2016 ; Infrastructure Completion Phase, Simulation Operation Stage, and Expanding Phase, from 2017 to 2020 and Accelerated Phase, from 2021 to 2025.

China's national carbon market has been operational for just over a year, marking the end of its first compliance cycle. During this period, several operational features of the national carbon market have come to light. These operational nuances form the basis for a legal analysis of the regulations governing the market and provide insight into existing challenges and potential solutions. The evolution of regional carbon markets over the years has led to the emergence of distinct trends in regional development. Studying these regional carbon markets contributes to understanding the regulatory impacts of laws and policies and provides valuable context. Notably, on July 16, 2021, China's National Emissions Trading Scheme (ETS) began trading on the Shanghai Environment and Energy Exchange (SEEE), positioning itself as a key policy tool for advancing short- and long-term green development goals.

Industry alignment across provinces and cities is somewhat uniform, reflecting regional variations in industry composition. However, there is a consistent inclusion of the eight most emissions-intensive sectors : electricity, chemicals, building materials, steel, non-ferrous metals, paper, and aviation. These sectors contribute significantly to carbon emissions and are treated comprehensively in all carbon markets, as shown in Table 2.1, with a shared focus on the power and industrial sectors.

Regarding total allowances allocated, Guangdong exceeds Hubei by almost two times, while it outperforms Beijing and Shanghai by an impressive four times (Hao and Yang, 2022) note. In addition, it is worth noting that Guangdong's carbon market is the only one to successfully implement a comprehensive allowance auction system and operate it consistently. This unique feature has received only limited attention from researchers, as Wang et al. (2022) explain, pointing out that the Guangdong market is China's most representative carbon market in China.

TABLE 1.1 – Emissions Exchanges in China

Region	Platform	Opening Date	Coverage
Beijing	Beijing Green Exchange (CBGEX)	28 November 2013	Power, heat, manufacturing, transportation, construction, public institutions, and universities.
Tianjin	Tianjin Climate Exchange (TCE)	26 December 2013	Power, heat, steel, chemicals, petrochemicals, oil and gas exploitation, and other key emissions industries.
Shanghai	Shanghai Environment and Energy Exchange (SHEEX)	26 December 2013	Industries involving steel, petrochemicals, chemicals, nonferrous metals, power, building materials, textiles, paper, rubber, chemical fiber, and more. Nonindustrial sectors include aviation, ports, airports, railways, commerce, hotels, finance, and others.
Guangdong	Guangzhou Emissions Exchange	19 December 2013	Sectors include cement, steel, power, and petrochemicals. Gradually expanded to more than 10 industrial sectors such as ceramics, textiles, nonferrous metals, plastics, and paper during the second phase.
Shenzhen	China Emissions Exchange (Shenzhen)	18 June 2013	The industrial sector, building sector, and transportation sector.
Hubei	China Hubei Emissions Exchange	12 April 2014	Steel, chemicals, cement, automobile manufacturing, power, nonferrous metals, glass, paper, and other high-energy-consuming and high-emissions industries.
Chongqing	Chongqing Carbon Emissions Trading Center	19 June 2014	Six high-energy-consuming industries : electrolytic aluminum, ferroalloys, calcium carbide, caustic, cement, and steel.
Fujian	Fujian Haixia Equity Exchange	22 December 2016	Power, steel, chemicals, petrochemicals, nonferrous metals, aviation, building materials, paper, ceramics, and more.

1.2 Research questions and thesis structure

1.2.1 Research Questions Addressed in the Thesis

With the aim of investigating in depth the complex interplay between environment, energy and finance, this thesis engages in a many-sided exploration. Through a series of systematic investigations, the following research questions are addressed, each contributing to a deeper understanding of the complex relationships that define this nexus. By looking at both emerging and established market economies, this undertaking aims to shed light on vital aspects of sustainable development and market interactions. The following subsections reveal these research questions in detail, each opening a window onto a distinct facet of the environment-energy-finance interrelationship. Through rigorous analysis and meticulous investigation, this study aims to expose the underlying dynamics and implications inherent in this nexus.

Research Questions Addressed in the Thesis

1. What is the asymmetric impact of stock market development on environmental quality, considering

energy efficiency in emerging market economies ?

- 2. How do carbon markets interact with changes in stock and energy markets in Europe and China, considering their distinct regulatory frameworks ?**
- 3. How do oil demand, supply, and associated risk shocks affect carbon markets ?**
- 4. Are carbon markets interconnected with key fossil fuel markets and global clean energy indices, and what implications does this have for risk assessment and portfolio management ?**

1.2.2 Contributions of the Thesis to the Field of Study

This thesis offers several notable contributions to the general field of study examining the complex interplay between environment, energy, and finance. Through the exploration of specific research questions, this study explores new, less explored areas, bringing new perspectives and enriching the existing body of knowledge. The following contributions highlight the importance of this research :

1. Understanding the relationship between stock market, energy, and carbon emissions in Emerging Markets : Studying the asymmetrical impacts of stock market development and energy efficiency on environmental quality in emerging economies contributes to a more nuanced understanding of the complexities inherent in these markets. By dissecting the roles of economic development and environmental regulations, this study provides a better understanding of sustainable development in these contexts.
2. Enhanced Insight into Carbon Market Dynamics : By analyzing the role of carbon markets in China and Europe, we gain a better understanding of their contribution to environmental goals. By examining the interactions between stock markets, energy commodities, and carbon markets, this research enriches our knowledge of effective strategies for achieving sustainability goals.
3. Comprehensive exploration of oil market effects : Examining the impact of oil supply, demand, and risk shocks on carbon markets, while taking into account the broader economic perspective of oil prices, offers a multidimensional view of the energy-environment nexus. This contribution broadens our understanding of how energy dynamics impact environmental and economic dimensions.
4. Insights into Market Interconnectedness : Using advanced models such as TVP-VAR and DCC GARCH, combined with the methodology of Diebold and Yilmaz (2014), this study provides insight into the dynamic interconnections between different markets. This contribution is invaluable for refining portfolio management and risk assessment strategies.

These contributions underline the relevance of this thesis to a wider field of study and open the way to further research and informed decision-making in the fields of sustainable development, market dynamics, and environmental policy.

1.2.3 Thesis structure

This thesis comprises four studies, each addressing unique dimensions of the complex link between finance, energy, and the environment. The first article focuses on investigating the Impact of stock market development and energy efficiency on carbon emissions. The second article delves into the links between stock market, the European /Chinese carbon market, and energy markets. The third article explores the response of carbon market to demand, supply, and risk shocks of oil prices. Lastly, the fourth article investigates the interconnectedness between European /Chinese carbon markets, fossil fuel energy markets, and major clean energy indices.

Article 1 : On the asymmetric relationship between stock market development, energy efficiency and environmental quality : A nonlinear analysis

As part of sustainable development and improved environmental performance, it is imperative to reduce and manage CO₂ emissions. Recently, a large body of research has examined the impact of financial development on environmental pollution, particularly in developed and emerging economies. In particular, some empirical studies have specifically examined the impact of stock markets on pollution. This research has revealed that the stock market can manifest two contrasting effects on environmental pollution, as explained in a selection of studies (Griffin et al., 2015; Zafar et al., 2019; Zhao and Yang, 2020). In addition, investors, particularly in emerging markets where climate finance initiatives remain fragmented, need up-to-date, reliable data on the financial performance of low-carbon investments. Accordingly, the first research study investigates the impact of stock market development and energy efficiency on carbon emissions in emerging market economies. To emphasize the importance of the research and improve our understanding of the interaction between the stock market, energy use and environmental quality, this study uses autoregressive distributed lag (ARDL) and nonlinear autoregressive distributed lag (NARDL) techniques, as developed initially by Shin et al. (2013), building on Schorderet's (2004) approach to modeling asymmetric cointegration through partial sum decomposition. In addition, it incorporates an asymmetric Granger causality methodology for panels, introduced by Granger (1988), to investigate bidirectional causality between the variables under study. Our study encompasses 19 emerging market economies and covers data from 1995 to 2014. This study is justified by the growing importance of understanding this relationship, given its potential implications for sustainable development.

Article 2 : Asymmetric connectedness among stocks, energy, and carbon emissions trading systems in Europe and China

Recently, numerous studies have supported the links between the carbon and stock markets (Ji et al., 2019; Li et al., 2021; Tan et al., 2020; Yuan and Yang, 2020). In addition, some researchers have investigated the asymmetric link between China's carbon and stock markets. Their findings indicate no substantial influence of the stock market on carbon prices. However, Y. Li et al (2020) identified a relatively small spillover effect between the Chinese carbon market and the electricity sector. These apparently contradictory results suggest the existence of hidden

factors that require further investigation. Venmans (2015) found a positive correlation between European allowance prices and the share prices of regulated companies. In addition, some researchers have undertaken cross-country comparisons of the links between carbon prices and stock markets. Motivated by this, We build on the existing literature by conducting a comprehensive review of the interaction between stock markets, oil prices, green bonds and carbon markets in Europe and China. To our knowledge, this study is pioneering in assessing the influence of stock markets on carbon markets, encompassing oil prices and green bonds in two distinct contexts. Our analysis uses the asymmetric GARCH BEKK model and the DCC model to investigate the interconnections between equity, energy and carbon markets in Europe and China. The data in our study covers the period between 2019 and 2021, which corresponds to the availability of carbon market data.

Article 3 : Asymmetric effects of decomposed oil-price shocks on carbon markets : Comparative analysis

To mitigate global warming, the Carbon Emissions Trading Scheme (ETS) has effectively promoted a transition to a low-carbon economy with minimal economic costs. The European Union Emissions Trading Scheme (EU ETS) is the world's first and largest carbon market (Ren et al., 2021). As China is a major carbon emitter, the efficiency of its carbon market has received increasing attention in recent years. Research into its effectiveness has multiplied (Zhao et al., 2016 ; Fan et al., 2018 ; Chen et al., 2021). Simultaneously, as a fundamental driver of economic and social activities, crude oil consumption influences carbon emissions through various channels, including energy supply in production and transportation, impacting carbon market dynamics (Dutta, 2018 ; Dong et al., 2021). Consequently, it is essential to fully understand the market interaction between crude oil and carbon allowances in both Europe and China . Nevertheless, there is no consensus on the presence and nature of this interaction (Ren et al., 2022). In addition, this study investigates the response of the carbon market to oil demand, supply and risk shocks using Ready's (2018) oil price decomposition method. In addition, it introduces a new dynamic perspective to assess changes in carbon market returns in response to demand, supply and risk shocks via the Bayesian SVAR TVP model. To capture key events, structural changes resulting from recent events such as the Russian-Ukrainian war, the Covid-19 pandemic and the crude oil crisis are taken into account. Our analysis covers data from January 2014 to March 2023.

Article 4 : The interconnectedness of carbon, fossil fuels, and renewable markets in the context of climate change

In the face of the growing danger of global warming, which translates into more frequent and severe natural disasters resulting in human and economic losses, the urgency of taking global action to combat the problem cannot be overstated (Le et al., 2023). To effectively combat global warming and promote sustainability, adopting a dual approach involving carbon markets and the expansion of renewable energy sources is vital. Carbon markets facilitate the reduction of emissions and the development of low-carbon technologies while guaranteeing cost-effective solutions (Liu et al., 2023). At the same time, developing renewable energy sources significantly contributes to sustainable, environmentally-friendly energy production (Nie et al., 2021). As Mo et al. (2022) point out, hedging

between the carbon market and the clean energy stock market has discernible short-term benefits. In the context of the Emissions Trading Scheme (ETS), Chun et al. (2022) found a negative correlation between carbon-concentrated fuel prices and clean energy company valuations. Their findings also revealed a contrasting relationship between coal prices and carbon prices. In a study by Wei et al. (2023), the interconnection between climate change, carbon emission allowances, renewables, and crude oil markets was explored. Their results suggest a relatively weak and fluctuating interconnection between the variables examined, with climate change as the main shock emitter. While Hammoudeh et al. (2014) demonstrated a negative relationship between carbon prices and crude oil and natural gas prices, Zeng et al. (2017) argued for a positive impact of energy prices on carbon prices. In light of these contradictory results, our study sheds light on the interconnectivity between three principal fossil energies : oil, coal, natural gas, the European/Chinese carbon market, and several clean energy indices. Using the TVP-VAR and DCC models in conjunction with Diebold and Yilmaz's (2012) connectivity model, this study focuses on gaining a deep understanding of the complex relationships between the markets studied. Through this analysis, the research study provides valuable insights into potential actions that investors, policymakers and regulators can take to advance environmental goals and optimize portfolio risk management.

Explanation of the Flow of the Thesis

The structure of this thesis is carefully designed to form a coherent and logical narrative, allowing a systematic exploration of the complex relationships within the link between environment, energy, and finance. The chapters are closely linked, each building on the foundations set by the preceding chapters. This deliberate arrangement ensures a harmonious progression of ideas and perspectives, collectively contributing to a comprehensive understanding of the multidimensional dynamics explored. Through the first study, we investigate the asymmetrical impact of stock market development on environmental quality in emerging market economies. This chapter examines the distinct dynamics of economies marked by economic growth and relatively weak environmental regulations. The information collected here provides an essential basis for understanding the complex interaction between financial markets, energy efficiency, and environmental sustainability.

Then, study 2 builds on the foundations laid in the previous chapter by examining the role of carbon markets in achieving environmental goals. The focus is on the specific cases of China and Europe, which have unique market characteristics and structures. This chapter enhances our understanding of regulatory efficiency and market linkages by analyzing the interactions between stock markets, energy commodities, and carbon markets.

Following this, it is a seamless transition to article 3, which looks at the complex dynamics of oil markets and their impact on carbon markets. By integrating the broader economic perspective of oil prices, this chapter offers a more holistic view of how energy markets impact the environmental and economic domains. The resulting insights help us to refine our understanding of sustainable energy strategies. The exploration continues in study 4, which examines the interconnectedness between different markets, including carbon markets, fossil fuel markets, and

global clean energy indices. This chapter uses advanced models to reveal the complex network of relationships and volatility transmissions. The information obtained here can be used to refine portfolio management and risk assessment strategies. The presentation ends with the general conclusion, in which the synthesized findings of the previous chapters are presented. This conclusion provides an overview of the main findings and their implications. By summarizing the complex relationships explored throughout the thesis, this conclusion offers a comprehensive perspective on the complex link between environment, energy, and finance. The interplay of each chapter contributes to a better understanding of the complex network of relationships that define our study, enhancing the understanding of sustainable development, market dynamics, and environmental policies in a larger field.

Chapitre 2

Introduction à l'Interconnexion entre Finance, Énergie et Environnement

Le changement climatique apparaît comme l'un des défis les plus importants et les plus cruciaux du 21^e siècle, jetant une ombre omniprésente et inquiétante sur les systèmes écologiques, économiques et sociaux. Ses effets considérables s'étendent au bien-être de chaque individu, ce qui souligne l'urgence de faire face à ses implications complexes. Au cours de la dernière décennie, l'ampleur et l'importance des stratégies d'adaptation au changement climatique ont connu une expansion remarquable. Ces stratégies, défendues par des organismes gouvernementaux opérant aux niveaux local, régional et mondial, visent à atténuer les conséquences écologiques, économiques et sociales considérables du changement climatique. L'initiative "Une planète propre pour tous" de l'Union européenne, élément clé du "Green Deal" européen, qui vise à décarboniser l'économie et à promouvoir la vitalité écologique (Commission européenne, 2018), illustre ces efforts. Alors que l'attention se porte sur les stratégies d'adaptation et d'atténuation du climat, l'exploration des dimensions équitables et du rôle complexe du secteur financier dans ce réseau multidimensionnel s'intensifie. Dans ce contexte, les économies émergentes et les pays à faible revenu se trouvent dans une situation paradoxale. Tout en contribuant moins proportionnellement à la cause première du problème, ces nations portent un fardeau disproportionnellement plus lourd en raison des externalités négatives résultant du changement climatique (GIEC 2022). Bien que les pays développés soient historiquement responsables de la plupart des émissions de gaz à effet de serre (GES) et des émissions par habitant, la réalisation des objectifs de stabilisation du climat nécessite des réductions d'émissions de la part des économies émergentes. En outre, ces économies sont particulièrement vulnérables aux effets du changement climatique, qui sont encore exacerbés par les vulnérabilités accrues découlant des pressions intenses exercées sur les systèmes écologiques locaux et régionaux (Gilding, 2011). Cette vulnérabilité est aggravée par les contraintes structurelles auxquelles sont confrontées les économies émergentes et les pays à faible revenu, notamment en termes de capacité économique et financière.

Ces contraintes entravent leur capacité à formuler et à mettre en œuvre efficacement des stratégies d'atténuation et d'adaptation au changement climatique (Dafermos, Nikolaidi 2019). Bien qu'apparemment mineurs, ces aspects sont d'une importance considérable pour déterminer l'efficacité de l'utilisation et de la gestion des ressources humaines.

Bien que ces aspects semblent mineurs, ils sont d'une importance considérable pour déterminer l'utilisation efficace et les risques associés aux actifs financiers que les pays en développement peuvent engager, comme le démontre la littérature sur le financement du développement (Raj 1998 ; Cohen et al. 2008). Les dimensions impliquant des ressources en capital exogènes et des relations financières complexes entre les pays sont depuis longtemps des questions controversées dans l'économie et la finance du développement (Raj 1998 ; Kregel 2004), ainsi que dans la macroéconomie postkeynésienne à orientation plus structurelle (Bonizzi 2017).

Le sujet central de cette thèse est l'exploration complète des liens complexes entre la finance, l'énergie, les émissions de carbone et le marché du carbone. Cette interaction complexe est essentielle pour relever les défis mondiaux à court et à long terme auxquels nous sommes confrontés. Les systèmes financiers, les marchés de l'énergie et surtout le marché du carbone étant de plus en plus étroitement liés, il devient essentiel d'étudier les liens qui existent entre ces marchés.

Toutefois, pour comprendre le contexte opérationnel de ces marchés, il faut avoir une compréhension fondamentale des origines, des fondements et des conséquences anticipées du changement climatique. Les liens étroits entre la finance, l'énergie, les émissions de carbone et le marché du carbone soulignent la nécessité d'une recherche approfondie sur les interactions à multiples aspects et les impacts potentiels. Les décisions financières et les modèles de consommation d'énergie exercent une influence significative sur les prix du carbone, tandis que les réglementations et les changements climatiques peuvent entraîner une nouvelle configuration des marchés de l'énergie, affecter les émissions de carbone et avoir un impact sur les performances financières.

Ainsi, ce premier chapitre de thèse ne sert pas seulement d'introduction, mais constitue également la base d'une étude approfondie de ces relations complexes. Les connaissances acquises ont des implications considérables pour la mise en place de politiques, les stratégies d'investissement, les initiatives de réduction des émissions de carbone et la recherche globale de la durabilité environnementale dans notre monde en constante évolution.

2.1 Contextualiser le lien entre l'environnement, l'économie et la finance

2.1.1 Exploration du changement climatique

Le contexte du changement climatique

Ces derniers temps, les concentrations de gaz à effet de serre dans l'atmosphère terrestre ont augmenté rapidement, en particulier le dioxyde de carbone. Cette augmentation des niveaux de dioxyde de carbone est principale-

ment due à la combustion du charbon, du pétrole et du gaz naturel, communément appelés "combustibles fossiles". À l'échelle mondiale, ces combustibles fossiles sont devenus une source d'énergie pratique pour les transports et la production d'électricité, ainsi qu'une source vitale de chaleur pour les habitations et les processus industriels. La déforestation généralisée a également contribué au changement climatique. En d'autres termes, lorsque les arbres arrivent à maturité, ils absorbent le dioxyde de carbone, puis libèrent des gaz à effet de serre lorsqu'ils sont abattus, puis brûlés ou laissés à l'abandon.

Aujourd'hui, les niveaux de dioxyde de carbone sont presque une fois et demie plus élevés qu'ils ne l'étaient pendant la révolution industrielle, il y a environ deux siècles. L'augmentation des niveaux de dioxyde de carbone entraîne une rétention accrue de la chaleur dans la planète, ce qui se traduit par une hausse de la température de la Terre. Ce phénomène, connu sous le nom de "réchauffement climatique", entraîne une augmentation générale des températures à la surface des terres et des océans. Le débat sur les mesures de lutte contre le changement climatique se concentre systématiquement sur le rôle essentiel des émissions de carbone dans le réchauffement de la planète et sur les conséquences qui en découlent. Les émissions de gaz à effet de serre, principalement sous la forme de dioxyde de carbone (CO₂) libéré dans l'atmosphère par les activités humaines telles que la production de combustibles fossiles, la déforestation et les processus industriels, sont au cœur des efforts déployés pour atténuer le changement climatique. L'accumulation de ces émissions entraîne un effet de serre, c'est-à-dire que certains gaz retiennent la chaleur dans l'atmosphère, ce qui entraîne une augmentation des températures globales. Par conséquent, la compréhension, la quantification et la gestion efficace des émissions de carbone sont devenues les éléments essentiels des stratégies d'atténuation du changement climatique. L'une des principales mesures des émissions de carbone est la concentration de CO₂ dans l'atmosphère. Cette mesure est suivie dans le temps à l'aide de données recueillies auprès de diverses sources, notamment des stations de surveillance, des satellites et des carottes de glace. La tendance continue à la hausse des concentrations de CO₂ dans l'atmosphère depuis la révolution industrielle souligne l'ampleur de l'impact de l'homme sur le système climatique de la planète. La courbe de Keeling, qui représente graphiquement cette augmentation des niveaux de CO₂ dans l'atmosphère, est un rappel brutal de la nécessité urgente de réduire les émissions de carbone.

L'atténuation des émissions de gaz à effet de serre implique des efforts pour réduire les émissions et renforcer les puits de carbone capables d'absorber le CO₂ de l'atmosphère. Cela signifie qu'il faut renoncer aux systèmes énergétiques basés sur les combustibles fossiles au profit d'alternatives plus propres et renouvelables telles que l'énergie solaire, l'énergie éolienne et l'énergie hydroélectrique. L'adoption de technologies à haut efficacité énergétique, de pratiques durables et de programmes de reforestation contribue également à la réduction des émissions de carbone. Divers accords internationaux, tels que l'Accord de Paris, ont souligné l'importance pour les pays de fixer et d'atteindre des objectifs de limitation des émissions de carbone, favorisant ainsi la réduction des émissions de gaz à effet de serre. des objectifs pour limiter les émissions de carbone, favorisant ainsi un engagement mondial pour lutter contre le changement climatique.

Les émissions de carbone sont intrinsèquement liées à la question la plus générale du développement durable. L'équilibre entre la croissance économique et la réduction des émissions est un défi complexe, en particulier pour les pays en développement fortement dépendants des combustibles fossiles. Les mesures politiques, les innovations technologiques et les aides financières peuvent jouer un rôle clé dans la facilitation de cette transition. En outre, la mesure des émissions de carbone constitue un indicateur tangible permettant d'évaluer l'efficacité des politiques climatiques et de suivre les progrès accomplis dans la réalisation des objectifs de réduction des émissions. En conclusion, la mesure et la gestion des émissions de carbone constituent la clé essentielle de la réponse internationale au changement climatique, témoignant d'une détermination collective à en atténuer les principaux facteurs et à assurer un avenir durable.

Impact du changement climatique sur les économies et les sociétés

Le changement climatique et la dégradation de l'environnement exercent une influence significative sur l'état d'une économie durable, impactant à la fois les institutions financières et non financières (Sullivan 2014; Ozili, 2020). Les effets négatifs potentiels du changement climatique sur les activités économiques deviennent évidents à travers les risques climatiques, qui ont des conséquences négatives sur le bien-être humain et les moyens de subsistance futurs. Pour gérer efficacement ces risques climatiques et remédier aux pertes et dommages qui en résultent, il faut une prise de décision sociétale, une gestion proactive et la capacité de prévoir les futures émissions de gaz à effet de serre et leurs implications pour le développement socio-économique et la justice sociale. La figure 1 illustre la relation entre les scénarios d'émissions et le réchauffement futur, en soulignant l'impact important du changement climatique sur la vie des différentes générations (nées en 1950, 1980 et 2020). Cette présentation souligne le rôle transformateur que peut jouer le changement climatique et sa capacité imminente à modifier le cours de la vie. Elle souligne également la responsabilité urgente qui incombe aux individus de réduire les émissions de gaz à effet de serre et d'orienter le cours des prochaines décennies vers un avenir durable et résilient.

L'activité humaine est l'un des principaux responsables du changement climatique et représente l'un des défis les plus urgents à relever au niveau mondial. De plus, la concentration de dioxyde de carbone dans l'atmosphère continue d'augmenter chaque année. Si l'énergie reste un moteur fondamental du progrès économique, répondre à l'évolution de la demande aux différents stades du développement économique nécessite des solutions durables aux problèmes environnementaux. La littérature existante met en évidence diverses approches et hypothèses concernant l'interaction entre la croissance économique et la pollution de l'environnement. D'une part, la recherche révèle que la qualité de l'environnement est influencée par les niveaux de revenu par habitant, ce qui entraîne des changements dans les politiques environnementales et crédibilise l'idée selon laquelle un revenu par habitant plus élevé est corrélé à une plus grande dégradation de l'environnement. D'autre part, il est considéré que la capacité à gérer le changement climatique dépend des niveaux de croissance économique ainsi que de la santé du secteur financier, de la structure des institutions, de la solidité des systèmes de santé et du niveau

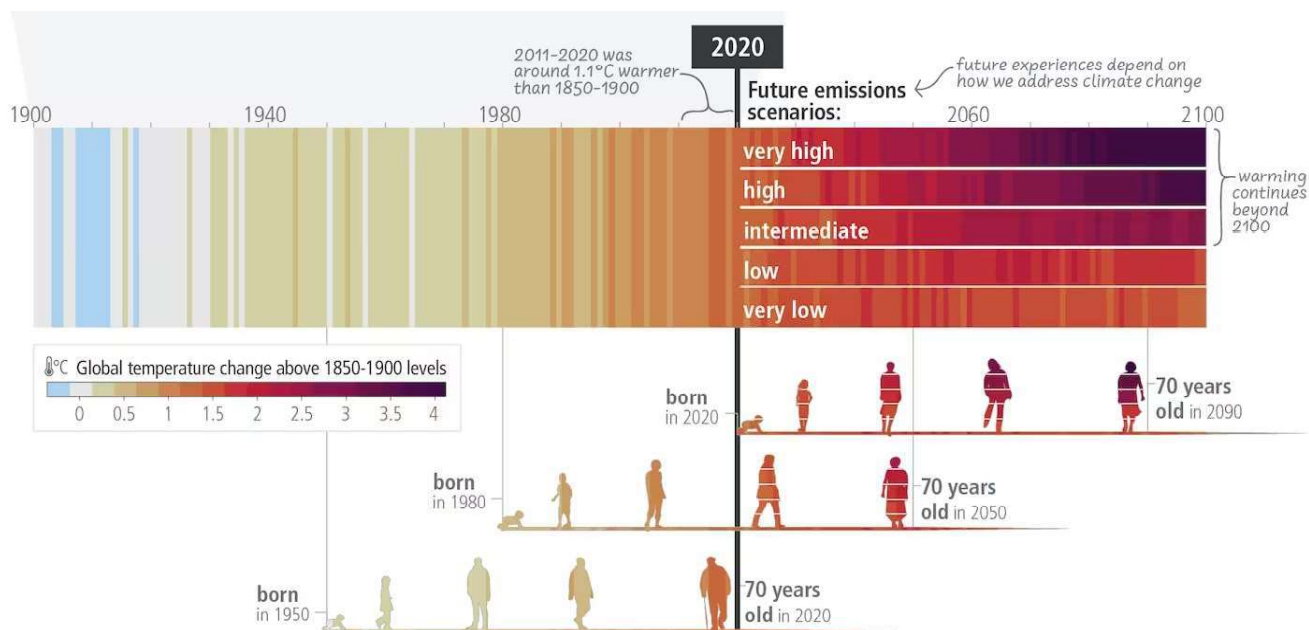


FIGURE 2.1 – Les choix climatiques : Bâtir notre avenir pour les générations à venir
 Source : Intergovernmental Panel on Climate Change 2020

d'éducation. Au cours des trente dernières années, une majorité de pays développés et plusieurs économies en développement se sont activement engagés dans la mise en œuvre de politiques de lutte contre la dégradation de l'environnement. À cet égard, l'Organisation de Coopération et de Développement Economiques (OCDE) a joué un rôle important, en contribuant régulièrement aux discussions et aux initiatives sur les politiques efficaces en matière de changement climatique. L'organisation a également démontré son efficacité dans l'évaluation des performances de ces politiques dans différents pays. Le Groupe d'experts intergouvernemental sur l'évolution du climat (GIEC) a également présenté des estimations suggérant que l'adoption d'approches économiquement efficaces basées sur le marché, telles que la tarification du carbone et l'échange de droits d'émission, pourrait conduire à des réductions relativement peu coûteuses des émissions de CO₂. Cette approche pourrait contribuer globalement aux efforts d'atténuation au niveau mondial (OCDE, 2007). Toutefois, si les coûts initiaux de ces mesures peuvent augmenter, les choix d'alternatives les moins efficaces, telles que la priorisation des instruments administratifs ou réglementaires ou l'exonération des activités à forte intensité énergétique ou des systèmes d'échange, pourraient s'avérer plus coûteux à long terme.

Pour réduire la proportion d'émissions de CO₂, il est nécessaire de modifier considérablement l'échelle et la composition de l'utilisation des énergies fossiles afin de réduire la teneur en carbone associée à la production et à la consommation de ces énergies. Une approche consiste à introduire une taxe carbone sur les énergies fossiles, déterminée en fonction de la teneur en carbone du combustible. Pearce (1991) a analysé la littérature existante sur les résultats potentiels des taxes sur le carbone. Barker et Lewney (1991) ont apporté des contributions notables à la modélisation macroéconomique des politiques environnementales, tandis que Sondheim (1991) a

particulièrement exploré les implications macroéconomiques des taxes sur le carbone. particulièrement exploré les implications macroéconomiques des taxes sur le carbone. Boero, Clarke et Winters (1991) ont fourni un examen complet des implications macroéconomiques à long terme de la réduction des émissions de gaz à effet de serre. Toutefois, aucune de ces études n'a examiné les effets d'une taxe sur le carbone sur les prix des produits industriels non combustibles, bien qu'une part importante des émissions de CO₂ provienne de la production de biens dans les activités industrielles.

De nombreuses mesures politiques peuvent être utilisées pour établir un mécanisme de tarification des émissions de CO₂, notamment les taxes sur le carbone ou l'énergie, la suppression des subventions nuisibles à l'environnement, les systèmes de quotas négociables et les mécanismes de flexibilité basés sur des projets décrits dans le Protocole de Kyoto à la convention-cadre des Nations unies sur les changements climatiques (CCNUCC) . Alors que la plupart des pays de l'OCDE ont mis en œuvre une ou plusieurs de ces mesures à des degrés divers, le principal défi consiste à étendre leur adoption et à les relier entre elles afin de créer un indicateur de prix cohérent et solide pour toutes les activités qui produisent de CO₂. L'introduction d'un prix international du carbone permet non seulement de réduire les coûts globaux associés aux émissions de CO₂, mais aussi d'uniformiser les règles du jeu entre les nations, en répondant aux préoccupations concernant les effets potentiels sur l'efficacité des politiques de conservation de l'environnement. Alors qu'un certain nombre de pays de l'OCDE ont institué des taxes sur l'énergie dans une certaine mesure, seule une minorité d'entre eux a imposé des taxes sur le carbone. Cette approche fiscale de la réduction des émissions de CO₂ peut être très rentable. Néanmoins, l'efficacité de ces mesures au sein de l'OCDE a souvent été réduite par l'octroi de remises ou d'exonérations de taxes sur l'énergie, principalement ciblées.

2.1.2 Perspectives scientifiques et risques économiques et financiers du changement climatique

Preuves scientifiques

Depuis le milieu des années 1800, les scientifiques ont reconnu le rôle essentiel du CO₂ en tant que principal gaz à effet de serre affectant le bilan énergétique de la Terre. Les mesures empiriques des niveaux de CO₂ dans l'atmosphère, y compris les données extraites des carottes de glace, démontrent une augmentation spectaculaire de 40% de la concentration de CO₂ dans l'atmosphère entre 1800 et 2019. L'examen de diverses formes de carbone, comme l'analyse isotopique, attribue sans équivoque cette augmentation aux activités humaines. En outre, les activités humaines contribuent également à l'augmentation des niveaux d'autres gaz à effet de serre, notamment le méthane et l'oxyde nitreux. L'augmentation perceptible des températures à la surface du globe depuis 1900 correspond parfaitement aux calculs précis évaluant l'impact de l'augmentation des gaz à effet de serre dans l'atmosphère, combinée à d'autres altérations d'origine humaine, sur l'équilibre énergétique de la Terre.

Les scientifiques pensent que le changement climatique anticipé est dû à la manière dont les gaz à effet de serre retiennent la chaleur. La compréhension fondamentale de la physique des gaz à effet de serre et les modèles distinctifs découverts dans les études d'empreintes digitales s'accordent sur le fait que les facteurs naturels ne suffisent pas à eux seuls à expliquer le changement climatique récent. Ces facteurs naturels comprennent les variations du rayonnement solaire, la dynamique orbitale de la Terre, les événements volcaniques et les fluctuations climatiques intrinsèques telles qu'El Niño et La Niña¹. Des modèles informatiques sophistiqués, configurés pour simuler les tendances de la température mondiale dues uniquement à ces facteurs naturels (Houghton, 2004), prévoient un réchauffement minime de la surface ou même un refroidissement marginal au cours des 20e et 21e siècles. Cependant, les changements de température observés s'alignent sur les modèles climatiques qui prennent en compte les changements de composition atmosphérique induits par l'homme.

En 2019, la concentration de CO₂ dans l'atmosphère terrestre a dépassé de 40% les niveaux observés au XIXe siècle. La majeure partie de cette augmentation s'est produite depuis 1970 environ, coïncidant avec une forte augmentation de la consommation mondiale d'énergie. Les mesures scientifiques ont montré une diminution des proportions d'autres isotopes du carbone, à savoir le ¹⁴C et le ¹³C, ainsi qu'une légère réduction de la concentration d'oxygène dans l'atmosphère, observée pour la première fois en 1990. Ces indicateurs montrent clairement que la source principale de l'augmentation du CO₂ est la consommation d'énergie fossile, caractérisée par de faibles proportions de ¹³C et une absence de ¹⁴C. En outre, les émissions de carbone dues à la déforestation et aux changements dans l'utilisation des terres ont contribué à libérer le carbone de la biosphère, où il réside naturellement pendant de longues périodes, généralement des décennies ou des siècles. Le CO₂ supplémentaire provenant de la combustion d'énergie fossile et de la déforestation a perturbé l'équilibre délicat du cycle du carbone. Malheureusement, les processus naturels capables de rétablir cet équilibre sont beaucoup plus lents que les taux rapides auxquels les activités humaines émettent du CO₂ dans l'atmosphère.

Par conséquent, une proportion importante du CO₂ généré par les activités humaines reste dans l'atmosphère, et une partie de ce CO₂ persiste non seulement pendant des décennies ou des siècles, mais aussi pendant des milliers d'années. Par rapport aux niveaux de CO₂ mesurés dans les carottes de glace, les concentrations atmosphériques actuelles sont nettement plus élevées qu'elles ne l'ont été depuis au moins 800 000 ans. Par conséquent, une proportion importante du CO₂ généré par les activités humaines reste dans l'atmosphère, et une partie de ce CO₂ persiste non seulement pendant des décennies ou des siècles, mais aussi pendant des milliers d'années, comme l'a confirmé l'Académie nationale des sciences (NAS). Par rapport aux niveaux de CO₂ mesurés dans les carottes de glace, les concentrations atmosphériques actuelles sont nettement plus élevées qu'elles ne l'ont été depuis au moins 800 000 ans. Alors que la persistance du CO₂ dans l'atmosphère se déploie sur de vastes échelles

1. El Niño et La Niña sont deux phases d'un phénomène climatique naturel connu sous le nom d'El Niño-Oscillation australe (ENSO). El Niño correspond à un réchauffement des températures de surface de la mer dans l'océan Pacifique, qui perturbe les schémas météorologiques mondiaux. En revanche, La Niña se caractérise par des températures de surface de la mer plus froides et a des effets contrastés sur les conditions météorologiques. Ces phénomènes ont un impact significatif à l'échelle mondiale, influençant les précipitations, les températures et les phénomènes météorologiques extrêmes dans diverses régions. Les scientifiques surveillent l'ENSO afin de prévoir les changements liés au climat et d'y répondre.

de temps, l'exploration qui s'ensuivra se concentrera sur les risques économiques et financiers étroitement liés à ces changements environnementaux, révélant ainsi l'interconnexion des défis posés par le changement climatique.

Risques économiques et financiers

Depuis sa création en 1988, le Groupe d'experts intergouvernemental sur l'évolution du climat (GIEC) a joué un rôle essentiel dans l'amélioration de notre compréhension de la réalité, de la portée et des causes sous-jacentes du changement climatique. Cette prise de conscience s'est progressivement étendue à une plus grande partie de la société et même aux décideurs politiques. Cependant, malgré la reconnaissance progressive des origines anthropogéniques du changement climatique par les décideurs politiques et les chefs d'entreprise du monde entier, le secteur financier est resté curieusement absent de ce discours pendant une longue période. Il est remarquable que ce contexte ait connu une transformation rapide au cours des dernières années. En relativement peu de temps, la finance s'est imposée comme un acteur essentiel du dialogue économique sur le changement climatique, s'alignant sur les principaux secteurs émetteurs de gaz à effet de serre (GES), notamment les énergies fossiles. Le texte suivant donne un aperçu de cette histoire concise, en se concentrant sur l'exposition du secteur financier aux risques liés au changement climatique.

Pendant longtemps, le secteur financier a essentiellement perçu le changement climatique comme une perturbation externe, analogue à une série de perturbations météorologiques ordinaires se produisant quotidiennement dans le monde entier. Il était généralement considéré comme un problème qui, s'il devenait un jour préoccupant, relèverait potentiellement du champ d'application des cadres de risque opérationnel, et ce uniquement si de graves conséquences se produisaient à l'horizon de plusieurs décennies. Pour le secteur financier, le changement climatique n'était pas considéré comme un problème urgent, mais plutôt comme une question à long terme devant être traitée par les décideurs politiques. Au début des années 2000, quelques institutions financières pionnières ont commencé à s'intéresser au changement climatique, mais à travers le prisme de leurs activités de financement de projets. Leur approche consistait principalement à évaluer les risques sociaux et environnementaux, en se concentrant sur les risques liés aux projets et leur impact sur l'environnement. Cette perspective initiale pourrait être caractérisée comme une forme de déni du changement climatique. L'une des principales motivations de ces pionniers était la pression croissante exercée par les organisations non gouvernementales (ONG) de défense de l'environnement sur les projets énergétiques très polluants. Leurs efforts étaient motivés par le désir de gérer les risques de réputation associés à ces projets.

L'étape suivante de cette évolution a été l'émergence des marchés du carbone, sous la pression du protocole de Kyoto. En 2005, cet accord international a ouvert la voie au système d'échange de quotas d'émission de l'Union européenne (EU-ETS), un mécanisme conçu pour allouer des quotas de carbone aux entreprises à des fins de conformité. Certaines institutions financières, en particulier les banques d'investissement, ont reconnu le potentiel des marchés du carbone comme une nouvelle voie de développement commercial. Elles ont intégré les activités

liées aux marchés du carbone à leurs bureaux de négociation d'énergie, améliorant ainsi leur compréhension du changement climatique et des politiques d'atténuation qui y sont associées.

L'émergence de l'investissement socialement responsable (ISR) au début des années 2000 a déclenché une prise de conscience des investisseurs à l'égard du changement climatique. D'abord défendue par les fonds de charité, cette prise de conscience s'est étendue aux fonds de pension et aux gestionnaires d'actifs axés sur l'ISR. La motivation sous-jacente de ce changement est double. Premièrement, elle était ancrée dans des considérations éthiques, reflétant un impératif moral de lutte contre le changement climatique. Deuxièmement, et plus important encore, elle découlait d'une perspective de gestion des risques qui, en principe, transcendait les limites de l'ISR. Cette perspective considère le changement climatique comme une source potentielle de risque financier, susceptible d'avoir un impact sur le rendement des investissements. En outre, elle reconnaît également le risque anticipé associé à une augmentation de la tarification du carbone induite par les politiques.

En suivant le cadre de Carney (2016), il est essentiel de souligner l'impact multidimensionnel du changement climatique sur les investisseurs, qui englobe trois canaux principaux : le risque physique, le risque de responsabilité et le risque de transition. Le premier canal, le risque physique, concerne les effets tangibles sur les actifs et les biens des risques climatiques de plus en plus graves, notamment les tempêtes, les incendies de forêt, les ouragans, les inondations et les sécheresses (Carney, 2016). Les effets tangibles du changement climatique sont déjà évidents dans les plans d'investissement mondiaux, les événements extrêmes liés au climat tels que les ouragans et les sécheresses introduisant une incertitude accrue pour les entreprises et les marchés financiers (BlackRock, 2015 ; Subramaniam, 2016). En l'absence de mesures d'atténuation rapides, le changement climatique est sur le point de remodeler le paysage économique mondial en amplifiant les vulnérabilités financières et en intensifiant les pertes économiques et humaines (Ricke et al., 2018). Les projections indiquent une augmentation de la fréquence des phénomènes météorologiques graves en raison du réchauffement de la planète (Forzieri et al, 2018), ce qui, à son tour, est susceptible d'entraîner une augmentation des dommages physiques et financiers résultant de ces événements.

La gestion de ces pertes a de multiples implications. Lorsque les pertes sont couvertes par l'assurance, elles ont un impact direct sur le secteur de l'assurance et de la réassurance, ce qui peut entraîner des pertes de portefeuille pour les compagnies d'assurance. Lorsque les pertes ne sont pas assurées, la responsabilité de la réparation des biens endommagés incombe aux propriétaires ou au gouvernement. Par exemple, le coût financier des ouragans aux États-Unis en 2017 a été estimé entre 65 et 190 milliards de dollars (Irfan, 2017). Selon Forzieri et al. (2018), l'impact des événements liés au climat devrait être multiplié par trois d'ici les années 2020 et par six d'ici le milieu du siècle, affectant principalement des secteurs tels que l'industrie, les transports et l'énergie. Des études récentes suggèrent que même avec une élimination complète des émissions de gaz à effet de serre, il reste peu probable que l'objectif de 2°Celsius soit atteint. Par conséquent, l'économie mondiale reste sensible aux impacts des événements physiques liés au climat, comme le souligne Raftery et al. (2017). En outre, des risques de responsabilité

apparaissent lorsque les parties touchées cherchent à obtenir une compensation pour les pertes attribuées à la hausse des impacts du changement climatique. Le nombre croissant de données scientifiques sur le climat devrait renforcer la réglementation climatique, comme le soulignent Marjanac et Patton (2018). Cette prolifération de la législation liée au climat à différents niveaux de gouvernance entraîne une augmentation des actions en justice contre les entreprises à forte intensité de carbone (Bloomberg, 2018). Les particuliers, les ONG et les organisations de la société civile touchés par le changement climatique peuvent demander une compensation financière à ceux qui sont jugés responsables de leurs pertes. Étant donné que les impacts climatiques extrêmes persistent, la fréquence de ces demandes d'indemnisation augmentera probablement à moyen et long terme. De nombreuses organisations non gouvernementales soutiennent activement ces efforts de sensibilisation à l'échelle mondiale. Un résultat découlant de ces risques de responsabilité pourrait déclencher un changement important dans les préférences des consommateurs, comme le suggèrent Schoenmaker et Schramade (2019). Ce changement, induit par l'évolution des modes de consommation des ménages et soutenu par l'intensification des campagnes publicitaires promouvant l'investissement responsable, représente un risque substantiel qui pourrait avoir un impact sur les modèles d'affaires des entreprises.

Le risque de transition implique la transformation potentielle d'une entreprise performante en une entreprise fragile en raison de changements brusques dans la politique ou la technologie. Ce risque est la conséquence de changements politiques et technologiques rapides rendus nécessaires par l'impératif de transition vers une économie résiliente et à faible émission de carbone. Par exemple, l'introduction de politiques respectueuses du climat visant à accélérer l'adoption de sources d'énergie renouvelables peut avoir un impact significatif sur l'évaluation des actifs financiers associés aux industries à forte intensité de carbone (Mercer, 2015 ; Battiston et al., 2017). Il est essentiel de souligner que ces risques ne sont pas de simples incidents, mais qu'ils sont interconnectés, complexes, non linéaires et qu'ils évoluent de manière dynamique. En outre, les politiques relatives au changement climatique, comme le souligne Guyatt (2011), représentent les facteurs de risque les plus critiques pour les investisseurs. En outre, les investisseurs peuvent subir des pertes résultant des conséquences indirectes du changement climatique. Selon Cahen-Fourot et al. (2021), tous les capitaux et installations industrielles qui dépendent des énergies fossiles subiront probablement les conséquences d'une transition rapide vers une économie à faible émission de carbone. En conséquence, le changement climatique est susceptible de nuire à la croissance économique et d'induire une instabilité politique, ce qui pourrait entraîner une baisse des rendements des investissements (De Nederlandsche Bank, 2017). Dans le domaine de la finance, ces risques sont appelés "risques de transition". Ces risques représentent les risques financiers associés à la transformation des secteurs énergétique et industriel dans le contexte de l'atténuation du changement climatique. Ces risques de transition ont de multiples aspects et proviennent de diverses sources, classées en risques politiques et juridiques, risques technologiques, risques de marché et risques de réputation, selon la définition de la Task Force on Climate-related Financial Disclosures (TCFD, 2017).

2.1.3 Marchés financiers et marchés des capitaux : Outils pour la résilience climatique et la durabilité

Le concept de durabilité

Le concept de durabilité est un concept multidimensionnel sujet à diverses interprétations, souvent influencé par des facteurs tels que les antécédents culturels, l'affiliation à des sociétés multinationales, la propriété de petites entreprises ou les efforts individuels pour définir un mode de vie durable (McNall et al., 2011). Cependant, il est loin d'être facile de définir précisément ce concept en raison de ses significations diverses et parfois contradictoires. Selon Agyekum Mensah et al. (2012), la durabilité en tant que concept a des origines relativement récentes, remontant à une conférence tenue dans les années 1970. De même, Kamara et al. (2006) affirment que la notion de durabilité a émergé de la Conférence des Nations Unies sur l'environnement humain (PNUE, 1972). La définition la plus largement acceptée du développement durable, résumée dans le rapport Brundtland de 1987, est la suivante "un développement qui répond aux besoins du présent sans compromettre la capacité des générations futures à répondre aux leurs propres besoins".

En adoptant cette définition, une compréhension plus profonde du concept de durabilité émerge, révélant sa complexité inhérente. S'inspirant principalement du rapport Brundtland, la dimension temporelle occupe le devant de la scène, englobant l'avenir immédiat et lointain. La reconnaissance d'une perspective intertemporelle est inhérente au développement durable, car elle tient compte de l'interconnexion complexe entre les actions actuelles et leurs répercussions potentielles sur de longues périodes de temps.

Ce concept de durabilité reflète les interconnexions complexes entre l'activité humaine et le bien-être environnemental. Alors que ce chapitre analyse le lien entre l'environnement, l'énergie et la finance, il est essentiel de reconnaître que la durabilité souligne la responsabilité de développer ce réseau complexe. Les multiples interprétations de la durabilité nous rappellent qu'il ne s'agit pas simplement d'un concept abstrait, mais d'un prisme à travers lequel nous voyons les complexités de nos choix, de nos systèmes et de notre environnement.

Renneboog et al. (2011) révèlent en outre que les fonds ISR, lorsqu'ils prennent en compte les rendements anormaux ajustés au risque, affichent une réduction annuelle moyenne des rendements d'environ 2% par rapport aux fonds conventionnels comparables. Cela suggère que les critères de sélection utilisés dans l'ISR introduisent des contraintes qui conduisent généralement à des rendements plus faibles. Toutefois, une exception à cette tendance est observée dans la catégorie sociale, où les résultats sont relativement mitigés. En outre, l'engagement dans l'activisme et la recherche interne en matière d'ISR sont susceptibles d'améliorer les rendements. Ces résultats soutiennent l'argument selon lequel le processus de sélection génère, dans certains cas, des informations pertinentes.

Le concept de résilience

Le concept de résilience a évolué de manière dynamique, comme une cible mouvante en constante redéfinition. Initialement, dans la théorie des systèmes, la résilience était étroitement définie comme la capacité d'un système à rebondir ou à revenir à l'équilibre après une perturbation, souvent appelée "résilience technique" (Holling, 1973). Toutefois, ce concept a évolué vers une notion plus complexe, la résilience dans les systèmes adaptatifs complexes allant au-delà de la simple résistance au changement et de la préservation des structures existantes (Folke, 2002), ce qui a conduit à la création d'un réseau d'experts en résilience et à la mise en place de mécanismes d'évaluation de la résilience dans les systèmes adaptatifs complexes.

Cette perspective développée englobe de multiples dimensions : (i) la capacité d'un système à s'adapter au changement tout en conservant sa fonction et sa structure ; (ii) le degré d'auto-organisation du système ; (iii) la capacité à améliorer l'apprentissage, l'adaptation et, le cas échéant, la transformation (Berkes et al., 2003). Dans ce concept, l'adaptabilité implique la capacité d'un système ou de ses composants à apprendre, à intégrer les connaissances et l'expérience, à ajuster les réponses aux facteurs externes et internes changeants et à continuer à se développer dans le cadre de la stabilité actuelle (Berkes et al., 2003). Inversement, la transformation implique la création d'un système fondamentalement nouveau lorsque les structures écologiques, économiques ou sociales existantes ne sont plus durables (Walker et al., 2004).

Outre la notion de capacité d'absorption ou de persistance, qui englobe diverses stratégies employées par les individus ou les ménages pour atténuer l'impact des chocs sur leurs moyens de subsistance et leurs besoins fondamentaux, trois dimensions fondamentales sont considérées comme des aspects essentiels de la résilience : la capacité d'absorption, la capacité d'adaptation et la capacité de transformation (Walker et al., 2004 ; Folke, 2006 ; Folke et al., 2010 ; Miller et al., 2010). Cette conceptualisation tridimensionnelle est intéressante car elle souligne que la résilience n'est pas le résultat d'une seule capacité, mais plutôt d'une interaction entre les trois.

En outre, ces différentes réponses peuvent être liées à différentes intensités de choc, l'efficacité des stratégies de résistance étant étroitement liée à l'intensité du choc initial. Lorsque l'intensité du choc initial est relativement faible, les systèmes sont plus susceptibles d'y résister efficacement, en absorbant ses effets sans conséquences perceptibles sur leur fonction, leur statut ou leur état. Norris et al. (2008) soulignent le résultat idéal de la résilience après une crise, affirmant que les ressources bloquent efficacement le facteur de risque, ce qui entraîne une absence quasi-totale de dysfonctionnement, quelle qu'en soit la durée. Ce concept s'étend au-delà des individus, car même les grands systèmes ont régulièrement recours à des stratégies de résilience. En outre, les stratégies de résistance sont pertinentes à plus grande échelle pour les risques prévisibles, tels que les incendies, qui peuvent être planifiés et atténués. Dans le cadre de la gestion des risques de catastrophes, de nombreux systèmes critiques sont délibérément conçus pour être résilients. Par exemple, les bâtiments résistants au feu et les sources d'énergie redondantes sont conçus pour permettre aux individus, aux communautés ou à des systèmes plus vastes

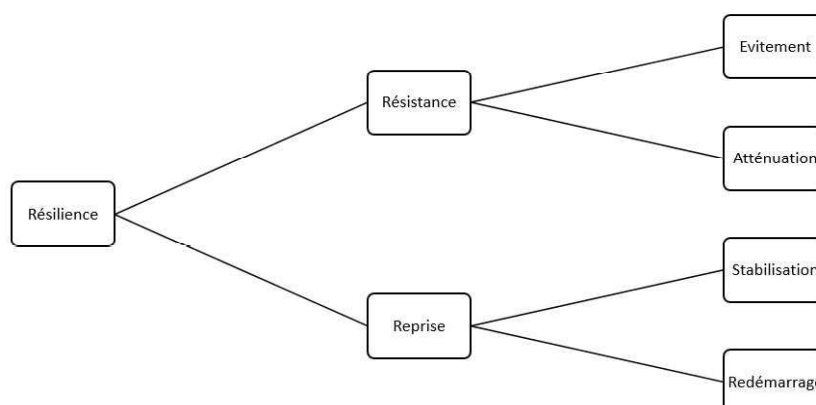


FIGURE 2.2 – La résilience en Management

de résister aux catastrophes. Lorsque la capacité d'absorption atteint ses limites, les individus doivent compter sur leur résilience adaptative, comme le proposent Cutter et al. (2008). La résilience adaptative comprend une série d'ajustements progressifs visant à maintenir la fonctionnalité sans subir de changements qualitatifs importants au niveau de la fonction ou de l'identité structurelle. Ces réponses adaptatives peuvent être individuelles ou collectives et intervenir à différents niveaux, du ménage à l'échelle de la communauté (Levine et al., 2011). En outre, l'adaptation semble être un processus continu et graduel qui peut être difficile à suivre ou à mesurer. Elle se produit souvent sans que les individus ou les sociétés ne réalisent pleinement comment ils s'adaptent à des circonstances changeantes (Levine et al., 2011). La résilience est un élément essentiel des marchés financiers, en particulier dans les pays émergents. Comme le souligne Bryan Pascoe, "nous devons accélérer le développement des marchés obligataires dans de nombreuses juridictions et régions, en particulier dans les économies émergentes". Cette accélération est essentielle pour renforcer la résilience structurelle et la profondeur des pays émergents afin qu'ils puissent répondre à leurs importants besoins de financement. Si les obligations de résilience représentent une première étape encourageante, elles occupent encore une position de substitution. Nous avons besoin d'une gamme plus large d'instruments de dette axés sur l'économie et la croissance pour parvenir à une plus grande résilience. La normalisation des instruments de marché joue un rôle clé dans la réduction des obstacles à l'investissement, favorisant ainsi un environnement financier plus résilient. Des recherches récentes menées entre 1995 et 2017 renforcent l'importance de la résilience climatique, en montrant qu'elle a un impact positif sur les notations de crédit dans les pays en développement. À l'inverse, la vulnérabilité climatique a une influence négative sur ces notations, ce qui met en évidence la profonde interconnexion entre la résilience financière et les considérations environnementales (Cevik et Tovar Jalles, 2020).

Investissement responsable et solutions climatiques

Renneboog et al. (2011) étudient le comportement des investisseurs éthiques, en particulier ceux qui investissent dans des fonds d'investissement socialement responsable (ISR). Ces investisseurs privilégient les aspects non financiers des fonds par rapport aux rendements négatifs passés. L'étude cherche à déterminer si les entrées et sorties de fonds ISR sont influencées par les performances passées des fonds et compare ce comportement à celui d'autres types de fonds. L'ensemble des données comprend 410 fonds d'actions ISR dans le monde entier entre 1992 et 2003. Les résultats révèlent que les investissements dans les fonds ISR sont moins sensibles aux performances passées négatives que les investissements dans d'autres types de fonds. En outre, ces réactions varient géographiquement et diffèrent selon la catégorie de l'ISR, y compris les fonds anti-perte, éthiques, sociaux et environnementaux. Cette hétérogénéité indique que les préférences des investisseurs varient dans ces domaines. Les flux de fonds ISR environnementaux montrent notamment une plus grande sensibilité aux rendements positifs passés, alors que les autres catégories présentent des sensibilités plus faibles. En outre, l'étude confirme que des entrées importantes ne correspondent pas à des rendements ultérieurs plus élevés, conformément à l'hypothèse d'un marché efficient.

Obligation verte : un actif financier ayant un impact significatif sur l'environnement

L'un des moyens de mettre en œuvre des investissements respectueux du climat est d'allouer des fonds à des obligations vertes. La catégorie d'instruments financiers connue sous le nom d'obligations vertes a été introduite en 2007/2008 grâce à une collaboration entre la banque suédoise Skandinaviska Enskilda Banken (SEB) et la Banque mondiale. SEB a envisagé les obligations vertes pour répondre à la demande croissante d'investissements orientés vers l'environnement afin d'encourager les initiatives durables et résilientes en matière d'atténuation du climat. Aujourd'hui, il existe toute une gamme d'obligations vertes, souvent appelées "obligations climatiques", dont l'objectif principal est de faciliter le financement de la transition vers une économie à faible émission de carbone. Ce qui caractérise les obligations vertes ou climatiques, c'est leur lien intrinsèque avec les solutions au changement climatique, qu'il s'agisse de réductions d'émissions, d'avancées technologiques, de projets d'énergie renouvelable ou de projets d'adaptation. Le marché actuel des émissions d'obligations vertes a explosé, atteignant 33,03 milliards de dollars en 2015, ce qui représente une croissance substantielle par rapport à sa valeur de 3,9 milliards de dollars en 2011 (Climate Bonds Initiative, 2015).

Les obligations vertes sont des instruments de financement par l'emprunt de projets concernant les énergies renouvelables, l'efficacité énergétique, les infrastructures à faible émission de carbone et l'utilisation durable des ressources (voir figure 2). Les investisseurs dans les obligations vertes sont principalement des gouvernements, des banques internationales, des fonds de pension et de grandes entreprises. Le site web de la Climate Bond Initiative encourage les obligations vertes en affirmant que le signal marketing favorable généré par une entreprise

verte l'emporte sur les coûts de transaction supplémentaires associés à l'émission d'obligations vertes. En effet, la recherche universitaire a affirmé que ces effets de signal peuvent produire des rendements positifs sur les marchés financiers.

Ces obligations comprennent une grande variété d'options, telles que les obligations vertes de détail (Holmes et Mabey, 2009), les obligations vertes d'entreprise (Helm, 2009), les obligations de la Banque verte d'investissement (Green Investment Bank Commission, 2010), les gilts verts (Holmes, 2010), les obligations vertes des banques multilatérales de développement (Veys, 2010), les obligations vertes sectorielles (IETA, 2010) et les obligations vertes d'infrastructure (Caldecott, 2010). En particulier, le concept d'obligations vertes manque de critères spécifiques ou de définitions universellement acceptées de ce qui est qualifié de "vert". Certaines obligations se disent vertes sans validation externe. Pour remédier à cette situation, un groupe d'investisseurs, d'émetteurs et de souscripteurs adhérant aux principes des obligations vertes a publié des lignes directrices volontaires pour l'émission d'obligations vertes (ICMA, 2015).

Ces lignes directrices préconisent des pratiques de transparence et de divulgation au sein du secteur. En outre, Clapp et al. (2015) suggèrent que la science du climat devrait jouer un rôle dans la vérification indépendante des références environnementales des obligations vertes. Pour améliorer l'efficacité du marché des obligations vertes et faire progresser notre compréhension du risque climatique, des critères clairs et rigoureux devraient être établis pour déterminer si un projet peut être qualifié d'obligation verte. Il faut souligner qu'il existe des lacunes dans la recherche sur les obligations vertes, en particulier en ce qui concerne l'analyse de la performance des portefeuilles d'obligations vertes.

L'intégration de la finance durable dans le développement économique

La durabilité est un concept à trois piliers : économique, environnementale et sociale, collectivement connues sous le nom de "triple bilan" (Elkington, 1997 ; Magon et al., 2018). La figure 3 ci-dessous illustre le concept de durabilité et ses trois dimensions. Le concept de triple bilan, introduit pour la première fois par Elkington (1997), est apparu en 1997 et souligne l'interconnexion inhérente des objectifs des entreprises avec les sociétés et les environnements dans lesquels elles opèrent. La durabilité économique concerne la capacité d'une entreprise à générer des ressources financières adéquates, garantissant une liquidité continue et des rendements durables à long terme (Steurer et Konrad, 2009). La durabilité environnementale est atteinte lorsque la consommation de ressources naturelles d'une entreprise reste inférieure à son taux de reconstitution tout en minimisant la production de déchets et les émissions (Vachon et Mao, 2008). La durabilité sociale est obtenue en soutenant activement la préservation et le développement des compétences et des capacités des générations actuelles et futures, en promouvant la santé et en cultivant des pratiques équitables et démocratiques au-delà des limites de l'organisation (McKenzie, 2004).

Le sommet mondial de 2002 sur le développement durable a été une occasion exceptionnelle, réunissant un



FIGURE 2.3 – Mécanisme d'investissement en obligations vertes

Source : ETEnergyWorld (Feb 16, 2021)

<https://energy.economictimes.indiatimes.com/news/renewable/opinion-green-bonding-for-recovery/80985453>

large groupe de participants, dont des chefs d'État et de gouvernement, des délégués nationaux, des dirigeants d'organisations non gouvernementales (ONG), des entreprises et d'autres groupes influents. Le sommet avait un objectif primordial : attirer l'attention du monde et mobiliser les efforts collectifs pour relever des défis considérables. Ces défis étaient centrés sur l'amélioration de la qualité de vie des populations et la préservation des ressources naturelles de notre planète. Il est essentiel de noter que le monde est confronté à un dilemme pressant caractérisé par une population croissante et une demande accrue de produits de première nécessité tels que la nourriture, l'assainissement, l'eau, l'énergie et la stabilité économique (Nations unies, 2002).

À la suite de la Conférence des Nations unies sur le développement durable en 2012, un événement capital qui a abouti à l'adoption de la déclaration politique "L'avenir que nous voulons", une attention particulière a été accordée aux mesures pratiques à prendre pour parvenir au développement durable. La conférence de Rio a réuni les États membres pour délibérer sur le lancement d'un effort de collaboration. Cet effort visait spécifiquement à élaborer un ensemble complet d'objectifs de développement durable (ODD) qui non seulement s'appuieraient sur les succès des objectifs du Millénaire pour le développement, mais s'aligneraient aussi harmonieusement sur le programme de développement post-2015 plus large, tel que défini par les Nations unies (2012).

Les entreprises sont de plus en plus considérées comme des contributeurs importants aux émissions de gaz à effet de serre et à l'épuisement des ressources environnementales, ce qui stimule la demande de pratiques respectueuses de l'environnement (Gadenne et al., 2009). Les parties prenantes et les réglementations ont poussé à l'adoption de stratégies respectueuses de l'environnement, faisant de la durabilité des entreprises un domaine de recherche de premier plan (Searcy et Buslovich, 2014). La responsabilité sociale des entreprises (RSE) englobe

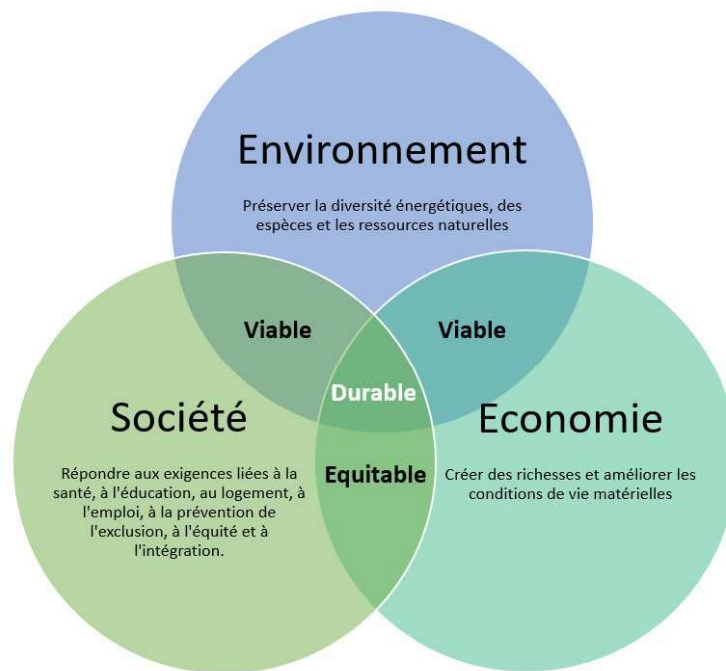


FIGURE 2.4 – Les piliers de la Durabilité

désormais la responsabilité environnementale, ce qui témoigne de sa reconnaissance mondiale (Yadav et Rho, 2016). La durabilité des entreprises aligne stratégiquement la productivité, la création de valeur et la compétitivité des entreprises sur les dimensions environnementales, économiques et sociales (Kocmanova et al., 2011).

Les chercheurs qui mènent des études sur les événements ont constaté que les entreprises respectueuses de l'environnement augmentent leur valeur, tandis que celles qui sont associées à des événements nuisibles à l'environnement perdent de la valeur (Flammer, 2013). Les organisations intègrent des initiatives écologiques dans leurs stratégies afin d'atténuer les risques environnementaux et d'améliorer potentiellement leurs performances financières, en fonction de leur secteur d'activité et des conditions environnementales. Dans ce contexte, les marchés du carbone sont apparus comme une solution importante pour lutter contre le changement climatique et réduire les émissions de carbone.

Marchés du carbone : Une solution au changement climatique

Les systèmes d'échange de quotas d'émission se caractérisent principalement par deux modèles distincts : les systèmes de plafonnement et d'échange et les systèmes de compensation.

Système de plafonnement et d'échange : Dans un système de plafonnement et d'échange, une autorité réglementaire fixe un plafond global ou une limite à la quantité totale d'émissions que toutes les entités participantes peuvent rejeter au cours d'une période donnée. Ce plafond est généralement réduit progressivement au fil du temps

pour atteindre les objectifs de réduction des émissions. Des quotas ou des permis d'émission, représentant chacun le droit d'émettre une certaine quantité de polluants, sont attribués à ces entités. Les entités qui émettent des polluants en dessous des quotas qui leur ont été attribués peuvent vendre leurs quotas excédentaires à celles qui les dépassent. Cela crée un marché pour l'échange des droits d'émission, où le prix des quotas est déterminé par l'offre et la demande. Le plafond garantit que les émissions globales restent dans la limite souhaitée, tandis que l'aspect commercial permet une certaine souplesse dans la réalisation des réductions.

Système de référence et de crédit : Dans un système de référence et de crédit, également connu sous le nom d'échange de crédits compensatoires, les entités reçoivent des crédits pour avoir entrepris des activités qui réduisent les émissions au-delà de ce qui est exigé par les réglementations. Ces crédits peuvent ensuite être vendus à des entités qui ont besoin de compenser leurs émissions. Le niveau de référence représente le niveau d'émissions attendu si aucune mesure n'était prise, et les crédits représentent la réduction obtenue. Ce système encourage l'innovation et les efforts supplémentaires pour réduire les émissions au-delà des exigences réglementaires. Toutefois, il nécessite un suivi rigoureux afin de s'assurer que les réductions d'émissions annoncées sont bien réelles.

Comme l'illustre la figure 4, dans un système de plafonnement et d'échange, une limite globale d'émissions est divisée en permis d'émissions individuels, chaque permis ETS représentant une tonne métrique de CO₂. Ces permis sont acquis et échangés entre les participants, en fonction des émissions résultant de leurs activités opérationnelles. Si un participant épuise ses permis, il doit soit acheter des permis supplémentaires auprès de ceux qui détiennent un excédent, soit cesser ses émissions.

Les systèmes d'échange de quotas d'émission comprennent trois éléments fondamentaux : (i) des plafonds fixant des limites absolues aux émissions : Ces plafonds fixent des limites strictes aux niveaux d'émissions autorisés pour les organisations participantes ; (ii) la valeur de rareté des quotas limités : La rareté des quotas leur confère une valeur intrinsèque, créant ainsi un coût déterminé par le marché pour les émissions de carbone. Ce mécanisme encourage les participants à réduire leurs émissions en adoptant des pratiques opérationnelles plus efficaces ou en investissant dans des technologies à faible émission de carbone ; (iii) l'échange de quotas pour des réductions rentables : Les organisations peuvent échanger des quotas, facilitant ainsi les réductions d'émissions de la manière la plus efficace sur le plan économique. Ce mécanisme d'échange permet aux entités d'optimiser leurs stratégies de réduction des émissions.

Le système d'échange de quotas d'émission de l'Union européenne (SEQE de l'UE) est l'exemple international le plus marquant d'un système de plafonnement et d'échange, qui a effectivement ouvert la voie à des efforts de réduction des émissions à l'échelle continentale. En outre, l'importance de l'échange de quotas d'émission dépasse les frontières de l'Europe, alors que la Chine se positionne comme un acteur central dans ce domaine. Les initiatives régionales chinoises en matière d'échange de quotas d'émission, qui englobent plusieurs provinces et villes, représentent une évolution cruciale dans les efforts mondiaux de lutte contre le changement climatique. En tant que premier émetteur mondial de gaz à effet de serre, l'engagement de la Chine en faveur de l'échange

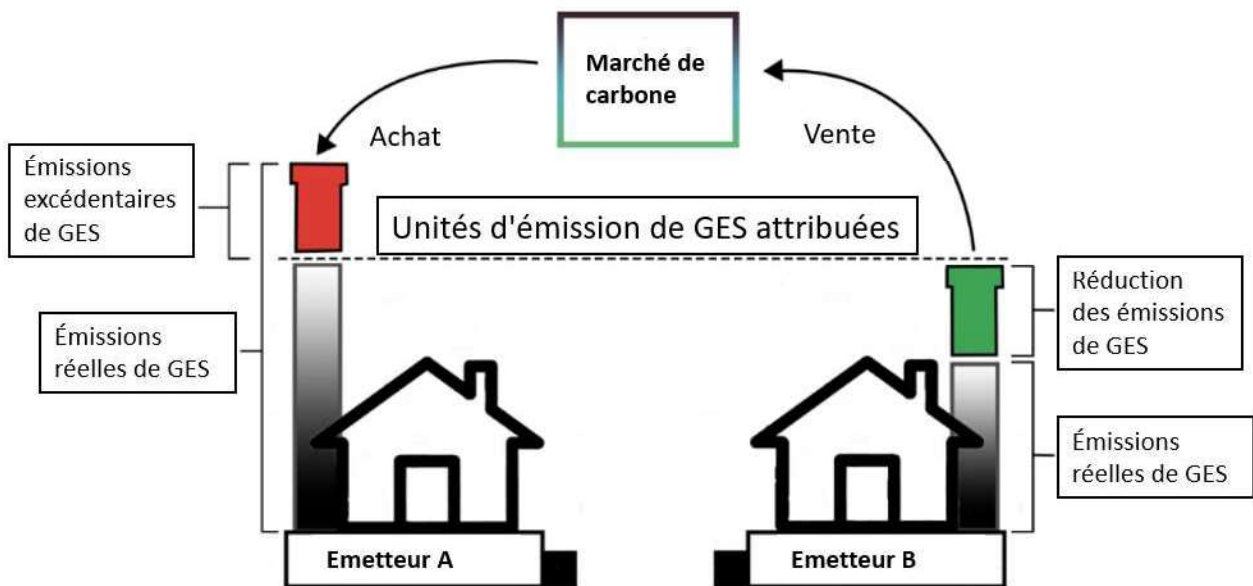


FIGURE 2.5 – Le système d'échange de droits d'émission de carbone

de droits d'émission démontre sa détermination à gérer l'environnement et peut influencer et façonner les marchés mondiaux du carbone.

Théorie économique des marchés du carbone

Pour stabiliser les niveaux de carbone dans l'atmosphère et atténuer le changement climatique, nos efforts ne doivent pas se limiter à la préservation des forêts, aux technologies énergétiques propres et aux stratégies de réduction des émissions. Il est essentiel de stimuler la demande du marché pour ces solutions cruciales, et les marchés du carbone apparaissent comme un moyen innovant et économiquement efficace d'atteindre ces objectifs multiples (Karmali, 2010). Ces marchés créent non seulement un attrait pour les crédits forestiers et les technologies énergétiques propres émergentes, mais introduisent également une valeur financière tangible pour les émissions, motivant les individus, les entreprises et les gouvernements à réduire leur empreinte carbone (Karmali, 2012).

Les marchés du carbone, caractérisés par leur nature dynamique et adaptative, sont conçus pour allouer efficacement les ressources aux méthodes les plus rentables de réduction des émissions de gaz à effet de serre (GES). Ils fonctionnent sur le principe de l'imposition de pénalités aux entités qui dépassent des limites d'émission prédéterminées, tout en récompensant celles qui émettent en dessous de ces seuils (Stern, 2006). Ce mécanisme fournit non seulement des incitations économiques à la réduction des émissions, mais encourage également l'innovation dans les technologies et les pratiques de réduction des émissions. En créant une approche du contrôle des émissions basée sur le marché, les marchés du carbone garantissent que les réductions d'émissions sont réalisées

de la manière la plus efficace et la plus économiquement durable.

Les marchés du carbone se distinguent également par leur nature inclusive. Ils invitent des participants tiers, y compris des spéculateurs et des investisseurs, à s'impliquer dans le processus. Ces acteurs jouent un rôle essentiel en facilitant l'investissement dans des initiatives respectueuses de l'environnement, accélérant ainsi la transition vers une économie à faibles émissions de carbone. En outre, les marchés du carbone encouragent un large panel de parties prenantes à s'impliquer. Les organisations environnementales, par exemple, peuvent jouer un rôle actif sur le marché en cherchant à réduire les émissions en deçà des objectifs réglementés. Pour ce faire, elles peuvent lever des fonds pour acheter et retirer des quotas d'émission, augmentant ainsi le coût des émissions et obligeant les émetteurs à améliorer leur efficacité opérationnelle (Bayon et al., 2007).

Système européen d'échange de quotas d'émission

Le système d'échange de quotas d'émission de l'Union européenne (SEQE de l'UE) est la plus grande initiative de marché du carbone au monde, couvrant un large panel de 10 000 installations. Celles-ci comprennent des centrales thermiques, des fours à coke, des raffineries d'huiles minérales, des unités de production et de traitement du fer, des exploitations minières et divers secteurs du verre, de la céramique, du papier et de la pâte à papier. Lancé en 2005, le système européen d'échange de quotas d'émission fonctionne comme un programme de plafonnement et d'échange, traitant près de la moitié des émissions de carbone de l'Union européenne (Soleille, 2006). Pour faciliter les activités d'échange et garantir le bon fonctionnement du marché, l'European Climate Exchange (ECX) sert de plateforme d'échange désignée. L'ECX joue un rôle essentiel dans l'amélioration de la liquidité du marché tout en offrant aux participants des avantages tels que la réduction des coûts de transaction, la minimisation des risques, la garantie de l'anonymat et la transparence des prix (Labbat et White, 2008).

Système chinois d'échange de quotas d'émission

Dans sa quête de pratiques environnementales durables et dans le cadre de son engagement à lutter contre le changement climatique, la Chine a développé des marchés régionaux du carbone. Ces initiatives régionales, souvent appelées "marchés pilotes" du carbone, représentent une phase essentielle de la stratégie plus large de la Chine visant à réglementer et à réduire les émissions de gaz à effet de serre. Contrairement à son équivalent européen, le système d'échange de quotas d'émission de l'Union européenne (SEQE de l'UE), les marchés régionaux du carbone de la Chine utilisent des mécanismes et des approches distincts. Les marchés pilotes du carbone ont joué un rôle clé dans la promotion d'un développement à faible intensité de carbone dans des secteurs vitaux tels que l'énergie, l'industrie, la construction et les transports. Ces initiatives ont permis d'établir les meilleures pratiques jugées dignes d'être reproduites et promues. Alors que ces marchés pilotes arrivaient à maturité, la Chine s'est engagée dans un voyage progressif vers le développement de son marché national du carbone, en passant par trois étapes distinctes d'évolution : La phase de préparation, de 2013 à 2016 ; la phase d'achèvement des infrastructures, la phase d'opération de simulation et la phase d'expansion, de 2017 à 2020 et la phase d'accélération, de 2021 à 2025.

Le marché national chinois du carbone est opérationnel depuis un peu plus d'un an, ce qui marque la fin de son premier cycle de conformité. Au cours de cette période, plusieurs caractéristiques opérationnelles du marché national du carbone ont été mises en évidence. Ces nuances opérationnelles constituent la base d'une analyse juridique des règlements régissant le marché et donnent un aperçu des défis existants et des solutions potentielles. L'évolution des marchés régionaux du carbone au fil des ans a conduit à l'émergence de tendances distinctes dans le développement régional. L'étude de ces marchés régionaux du carbone contribue à la compréhension des impacts réglementaires des lois et des politiques et fournit un contexte précieux. Notamment, le 16 juillet 2021, le système national chinois d'échange de quotas d'émission a commencé à être négocié à la Bourse de l'environnement et de l'énergie de Shanghai (SEEE), se positionnant comme un outil politique clé pour faire avancer les objectifs de développement vert à court et à long terme.

L'alignement des industries entre les provinces et les villes est relativement uniforme, ce qui reflète les variations régionales dans la composition des industries. Toutefois, les huit secteurs à plus forte intensité d'émissions sont systématiquement inclus : l'électricité, les produits chimiques, les matériaux de construction, l'acier, les métaux non ferreux, le papier et l'aviation. Ces secteurs contribuent de manière significative aux émissions de carbone et sont traités de manière globale sur tous les marchés du carbone, comme le montre le tableau 2.1, l'accent étant mis sur les secteurs de l'électricité et de l'industrie.

En ce qui concerne le total des quotas alloués, Guangdong dépasse Hubei de près de deux fois, tandis qu'il surpasse Beijing et Shanghai d'un impressionnant quadruple (Hao et Yang, 2022). En outre, il convient de noter que le marché du carbone de Guangdong est le seul à mettre en œuvre avec succès un système complet de vente aux enchères de quotas et à le faire fonctionner de manière cohérente. Cette caractéristique unique n'a reçu qu'une attention limitée de la part des chercheurs, comme l'expliquent Wang et al. (2022), qui soulignent que le marché de Guangdong est le marché du carbone le plus représentatif de Chine.

2.2 Questions de recherche et structure de la thèse

2.2.1 Questions de recherche abordées dans la thèse

Dans le but d'étudier en profondeur l'interaction complexe entre l'environnement, l'énergie et la finance, cette thèse s'engage dans une exploration à multiples volets. Grâce à une série d'investigations systématiques, les questions de recherche ci-après sont abordées, chacune contribuant à une compréhension plus approfondie des relations complexes qui définissent ce lien. En examinant les pays émergents et L'Europe, cette thèse vise à mettre en lumière les aspects essentiels du développement durable et des interactions entre les marchés. Les sous-sections suivantes présentent en détail ces questions de recherche, chacune ouvrant une fenêtre sur une dimension distincte de la relation entre l'environnement, l'énergie et la finance. Grâce à une analyse rigoureuse et à une enquête

méticuleuse, cette étude vise à mettre en lumière les dynamiques et les implications sous-jacentes inhérentes à ce lien.

questions de recherche abordées dans la thèse

- 1. Quel est l'impact asymétrique du développement des marchés boursiers sur la qualité de l'environnement, compte tenu de l'efficacité énergétique dans les pays émergents ?**
- 2. Comment les marchés du carbone interagissent-ils avec les variations des marchés boursiers et énergétiques en Europe et en Chine, compte tenu de leurs cadres réglementaires distincts ?**
- 3. Comment la demande et l'offre de pétrole et les chocs de risques associés affectent-ils les marchés du carbone ?**
- 4. Les marchés du carbone sont-ils interconnectés avec les principaux marchés des énergies fossile et les indices des énergies propres au niveau mondial, et quelles sont les implications pour l'évaluation des risques et la gestion des portefeuilles ?**

2.2.2 Contributions de la thèse

Cette thèse offre plusieurs contributions considérables au sujet général de l'étude de l'interaction complexe entre l'environnement, l'énergie et la finance. Grâce à l'exploration de questions de recherche spécifiques, cette étude explore de nouveaux aspects moins étudiés, apportant de nouvelles perspectives et enrichissant le champ de connaissances existant. Les contributions suivantes soulignent l'importance de cette recherche :

1. Compréhension de la relation entre le marché boursier, l'énergie et les émissions de carbone dans les marchés émergents : L'étude des impacts asymétriques du développement des marchés boursiers et de l'efficacité énergétique sur la qualité de l'environnement dans les pays émergents contribue à une compréhension plus nuancée des complexités de ces marchés. En analysant les rôles du développement économique et des réglementations environnementales, cette étude permet de mieux comprendre le développement durable dans ces contextes.
2. Compréhension approfondie de la dynamique des marchés du carbone : En analysant le rôle des marchés du carbone en Chine et en Europe, nous acquérons une meilleure compréhension de leur contribution aux objectifs environnementaux. En examinant les interactions entre les marchés boursiers, les énergies et les marchés du carbone, cette recherche enrichit nos connaissances sur les stratégies efficaces pour atteindre les objectifs de durabilité.
3. Exploration approfondie des effets du marché pétrolier : L'examen de l'impact des chocs de l'offre et de la demande ainsi que des risques liés au pétrole sur les marchés du carbone, tout en prenant en compte la perspective économique des prix du pétrole, offre une vision multidimensionnelle de la relation entre la

consommation, la production de pétrole, les activités financières des entreprises pétrolières et l'environnement. Cette contribution permet de mieux comprendre l'incidence de la dynamique énergétique sur les aspects environnementaux et économiques.

4. Compréhension de l'interconnexion des marchés : En utilisant des modèles avancés tels que le TVP-VAR et le DCC GARCH, combinés à la méthodologie de Diebold et Yilmaz (2014), notre étude donne un aperçu des interconnexions dynamiques entre les différents marchés. Cette contribution est essentielle pour améliorer la gestion des portefeuilles et les stratégies d'évaluation des risques.

Ces contributions soulignent la pertinence de cette thèse pour un champ d'étude plus large et ouvrent la voie à d'autres recherches et à une prise de décision réfléchie dans les domaines du développement durable, de la dynamique des marchés et de la politique environnementale.

2.2.3 Structure de la thèse

Cette thèse comprend quatre études, chacune abordant des dimensions uniques du lien complexe entre la finance, l'énergie et l'environnement. Le premier article se concentre sur l'étude de l'impact du développement des marchés boursiers et de l'efficacité énergétique sur les émissions de carbone. Le deuxième article étudie les liens entre les marchés boursiers, le marché européen du carbone, le marché chinois du carbone et les marchés de l'énergie. Le troisième article explore la réponse du marché du carbone aux chocs de demande, d'offre et de risque des prix du pétrole. Enfin, le quatrième article étudie l'interconnexion entre les marchés européens et chinois du carbone, les marchés de l'énergie fossile et les principaux indices d'énergie propre.

Article 1 : On the asymmetric relationship between stock market development, energy efficiency and environmental quality : A nonlinear analysis

Dans le cadre du développement durable et de l'amélioration des performances environnementales, il est impératif de réduire et de gérer les émissions de CO₂. Récemment, de nombreuses recherches ont examiné l'impact du développement financier sur la pollution de l'environnement, en particulier dans les économies développées et émergentes. Certaines études empiriques ont notamment examiné l'impact des marchés boursiers sur la pollution. Ces recherches ont révélé que le marché boursier peut avoir deux effets opposés sur la pollution environnementale, comme l'explique une sélection d'études (Griffin et al., 2015 ; Zafar et al., 2019 ; Zhao et Yang, 2020). En outre, les investisseurs, en particulier dans les pays émergents où les initiatives de financement climatique restent fragmentées, ont besoin de données actualisées et fiables sur la performance financière des investissements à faible intensité de carbone.

Par conséquent, la première étude examine l'impact du développement du marché boursier et de l'efficacité énergétique sur les émissions de carbone dans les économies de marché émergentes. Pour souligner l'importance de la recherche et améliorer notre compréhension de l'interaction entre le marché boursier, la consommation d'éner-

gie et la qualité de l'environnement, cette étude utilise les méthodes de retard échelonné autorégressif (ARDL) et de retard échelonné autorégressif non linéaire (NARDL), développées initialement par Shin et al. (2013), en s'appuyant sur l'approche de Schorderet (2004) pour modéliser la cointégration asymétrique par le biais de la décomposition de la somme partielle. En outre, elle intègre une méthodologie de causalité de Granger asymétrique pour les panels, introduite par Granger (1988), afin d'étudier la causalité bidirectionnelle entre les variables étudiées. Notre étude englobe 19 pays émergents et couvre les données de 1995 à 2014. Cette étude se justifie par l'importance accrue de comprendre cette relation, compte tenu de ses implications potentielles pour le développement durable.

Article 2 : Asymmetric connectedness among stocks, energy, and carbon emissions trading systems in Europe and China Récemment, de nombreuses études ont confirmé les liens entre les marchés du carbone et les marchés boursiers (Ji et al., 2019 ; Li et al., 2021 ; Tan et al., 2020 ; Yuan et Yang, 2020). En outre, certains chercheurs ont étudié le lien asymétrique entre les marchés du carbone et les marchés boursiers chinois. Leurs conclusions indiquent que le marché boursier n'a pas d'influence significative sur les prix du carbone. Cependant, Y. Li et al. (2020) ont identifié un effet d'entraînement relativement faible entre le marché chinois du carbone et le secteur de l'électricité. Ces résultats apparemment contradictoires suggèrent l'existence de facteurs cachés qui nécessitent un examen plus approfondi. Venmans (2015) a constaté une corrélation positive entre les prix des quotas européens et les cours des actions des entreprises réglementées. En outre, certains chercheurs ont entrepris des comparaisons entre pays des liens entre les prix du carbone et les marchés boursiers. Motivés par ce constat, nous nous appuyons sur la littérature existante en réalisant une étude complète de l'interaction entre les marchés boursiers, les prix du pétrole, les obligations vertes et les marchés du carbone en Europe et en Chine. À notre connaissance, cette étude est la plus innovante dans l'évaluation de l'influence des marchés boursiers sur les marchés du carbone, englobant les prix du pétrole et les obligations vertes dans deux contextes distincts. Notre analyse utilise le modèle GARCH-BEKK asymétrique et le modèle DCC pour étudier les interconnexions entre les marchés des actions, de l'énergie et du carbone en Europe et en Chine. Les données de notre étude couvrent la période entre 2019 et 2021, qui correspond à la disponibilité des données sur le marché du carbone.

Article 3 : Asymmetric effects of decomposed oil-price shocks on carbon markets : Comparative analysis Pour atténuer le réchauffement climatique, le système d'échange de quotas d'émission de carbone (SCEQE) a efficacement favorisé la transition vers une économie à faible émission de carbone avec des coûts économiques minimes. Le système d'échange de quotas d'émission de l'Union européenne est le premier et le plus grand marché du carbone au monde (Ren et al., 2021). La Chine étant l'un des principaux émetteurs de carbone, l'efficacité de son marché du carbone a fait l'objet d'une attention croissante ces dernières années. Les recherches sur son efficacité se sont multipliées (Zhao et al., 2016 ; Fan et al., 2018 ; Chen et al., 2021). Simultanément, en tant que moteur fondamental des activités économiques et sociales, la consommation de pétrole brut influe sur les émissions de carbone par divers canaux, notamment l'approvisionnement en énergie dans la production et le transport, ce qui a un impact sur la dynamique du marché du carbone (Dutta, 2018 ; Dong et al., 2021).

Par conséquent, il est essentiel de bien comprendre l'interaction entre le marché du pétrole brut et celui des quotas de carbone, en Europe comme en Chine. Néanmoins, il n'y a pas de consensus sur la présence et la nature de cette interaction (Ren et al., 2022). Cette étude examine en outre la réponse du marché du carbone aux chocs de la demande, de l'offre et du risque pétroliers en utilisant la méthode de décomposition du prix du pétrole de Ready (2018). Nous introduisons une nouvelle perspective dynamique pour évaluer les variations des rendements du marché du carbone en réponse aux chocs de demande, d'offre et de risque par le biais du modèle SVAR TVP bayésien. Pour saisir les événements clés, les changements structurels résultant d'événements récents tels que la guerre russo-ukrainienne, la pandémie de Covid-19 et la crise du pétrole brut sont pris en compte. Notre analyse couvre les données de janvier 2014 à mars 2023.

Article 4 : The interconnectedness of carbon, fossil fuels, and renewable markets in the context of climate change Face au danger croissant du réchauffement climatique, qui se traduit par des catastrophes naturelles plus fréquentes et plus graves entraînant des pertes humaines et économiques, il est impératif de prendre des mesures au niveau mondial pour lutter contre ce problème (Le et al., 2023). Pour lutter efficacement contre le réchauffement climatique et promouvoir la durabilité, il est essentiel d'adopter une double approche impliquant les marchés du carbone et l'expansion des ressources énergétiques renouvelables. Les marchés du carbone facilitent la réduction des émissions et le développement de technologies à faible émission de carbone tout en garantissant des solutions rentables (Liu et al., 2023). Parallèlement, le développement des sources d'énergie renouvelables contribue de manière significative à la production d'énergie durable et respectueuse de l'environnement (Nie et al., 2021). Comme le soulignent Mo et al. (2022), la couverture entre le marché du carbone et le marché boursier des énergies propres présente des avantages identifiables à court terme. Dans le contexte du système d'échange de quotas d'émission (ETS), Chun et al. (2022) ont constaté une corrélation négative entre les prix des combustibles concentrés en carbone et les évaluations des entreprises d'énergie propre. Leurs conclusions ont également révélé une relation contrastée entre les prix du charbon et les prix du carbone. L'étude de Wei et al. (2023) explore l'interconnexion entre le changement climatique, les quotas d'émission de carbone, les énergies renouvelables et les marchés du pétrole brut. Leurs résultats suggèrent une interconnexion relativement faible et fluctuante entre les variables examinées, le changement climatique étant le principal émetteur de chocs. Alors que Hammoudeh et al. (2014) ont démontré une relation négative entre les prix du carbone et les prix du pétrole brut et du gaz naturel, Zeng et al. (2017) ont affirmé que les prix de l'énergie avaient un impact positif sur les prix du carbone. À la lumière de ces résultats contradictoires, notre étude met en lumière l'interconnectivité entre les trois principales énergies fossiles : le pétrole, le charbon, le gaz naturel, le marché européen/chinois du carbone et plusieurs indices d'énergie propre. En utilisant les modèles TVP-VAR et DCC en combinaison avec le modèle de connectivité de Diebold et Yilmaz (2012), cette étude se concentre sur une compréhension approfondie des relations complexes entre les marchés étudiés. Grâce à cette analyse, l'étude fournit des indications précieuses sur les actions potentielles que les investisseurs, les décideurs politiques et les régulateurs peuvent mener pour faire avancer les objectifs

environnementaux et optimiser la gestion du risque de portefeuille.

Explication du cheminement de la thèse

La structure de cette thèse est soigneusement conçue pour former un récit cohérent et logique, permettant une exploration systématique des relations complexes entre l'environnement, l'énergie et la finance. Les chapitres sont étroitement liés, chacun s'appuyant sur les fondements établis par les chapitres précédents. Cette disposition délibérée garantit une progression harmonieuse des idées et des perspectives, contribuant collectivement à une compréhension globale des dynamiques multidimensionnelles explorées. Dans la première étude, nous examinons l'impact asymétrique du développement des marchés boursiers sur la qualité de l'environnement dans les pays émergents. Ce chapitre examine les dynamiques distinctes des économies marquées par la croissance économique et des réglementations environnementales relativement faibles. Les informations recueillies ici fournissent une base essentielle pour comprendre l'interaction complexe entre les marchés financiers, l'efficacité énergétique et la durabilité environnementale. Ensuite, l'étude 2 s'appuie sur les bases posées dans le chapitre précédent en examinant le rôle des marchés du carbone dans la réalisation des objectifs environnementaux. L'accent est mis sur les cas spécifiques de la Chine et de l'Europe, qui présentent des caractéristiques et des structures de marché uniques. Ce chapitre améliore notre compréhension de l'efficacité réglementaire et des liens entre les marchés en analysant les interactions entre les marchés boursiers, les matières premières énergétiques et les marchés du carbone.

Ensuite, la continuité est assurée avec l'article 3, qui examine la dynamique complexe des marchés pétroliers et leur impact sur les marchés du carbone. En intégrant la perspective économique plus large des prix du pétrole, ce chapitre offre une vision plus holistique de l'impact des marchés de l'énergie sur les domaines environnementaux et économiques. Les informations qui en résultent nous aident à affiner notre compréhension des stratégies énergétiques durables. L'exploration se poursuit dans l'étude 4, qui examine l'interconnexion entre différents marchés, notamment les marchés du carbone, les marchés des combustibles fossiles et les indices mondiaux de l'énergie propre. Ce chapitre utilise des modèles avancés pour révéler le réseau complexe de relations et de transmissions de volatilité. Les informations obtenues ici peuvent être utilisées pour affiner les stratégies de gestion de portefeuille et d'évaluation des risques. La présentation se termine par la conclusion générale, dans laquelle les résultats synthétisés des chapitres précédents sont présentés. Cette conclusion donne un aperçu des principaux résultats et de leurs implications. En résumant les relations multiples explorées tout au long de la thèse et offre une perspective globale sur le lien complexe entre l'environnement, l'énergie et la finance. L'interaction de chaque chapitre contribue à une meilleure compréhension du réseau de cette relations qui définissent notre étude, améliorant la compréhension du développement durable, de la dynamique du marché et des politiques environnementales dans un domaine plus large.

TABLE 2.1 – Échanges de droits d'émission en Chine

Région	Plateforme	Date d'ouverture	Couverture
Pékin	Bourse Verte de Pékin (CBGEX)	28 novembre 2013	Énergie, chauffage, fabrication, transport, construction, institutions publiques et universités.
Tianjin	Bourse du Climat de Tianjin (TCE)	26 décembre 2013	Énergie, chauffage, acier, produits chimiques, pétrochimie, exploitation pétrolière et gazière, et autres industries émettrices clés.
Shanghai	Bourse de l'Environnement et de l'Énergie de Shanghai (SHEEEX)	26 décembre 2013	Industries liées à l'acier, la pétrochimie, les produits chimiques, les métaux non ferreux, l'énergie, les matériaux de construction, les textiles, le papier, le caoutchouc, les fibres chimiques, et plus encore. Les secteurs non industriels incluent l'aviation, les ports, les aéroports, les chemins de fer, le commerce, les hôtels, la finance et d'autres.
Guangdong	Bourse des Émissions de Guangzhou	19 décembre 2013	Les secteurs comprennent le ciment, l'acier, l'énergie, et la pétrochimie. Progressivement étendu à plus de 10 secteurs industriels tels que la céramique, les textiles, les métaux non ferreux, les plastiques et le papier lors de la deuxième phase.
Shenzhen	Bourse des Émissions de Chine (Shenzhen)	18 juin 2013	Le secteur industriel, le secteur du bâtiment et le secteur des transports.
Hubei	Bourse des Émissions de Hubei en Chine	12 avril 2014	Acier, produits chimiques, ciment, fabrication automobile, énergie, métaux non ferreux, verre, papier, et d'autres industries à forte consommation d'énergie et émissions élevées.
Chongqing	Centre d'Échanges sur les Émissions de Carbone de Chongqing	19 juin 2014	Six industries à forte consommation d'énergie : aluminium électrolytique, ferroalliages, carbure de calcium, caustique, ciment et acier.
Fujian	Bourse de l'Équité de Haixia de Fujian	22 décembre 2016	Énergie, acier, produits chimiques, pétrochimie, métaux non ferreux, aviation, matériaux de construction, papier, céramique, et plus encore.

Chapitre 3

On the asymmetric relationship between stock market development, energy efficiency, and environmental quality : A nonlinear analysis

Abstract ¹

It has been widely documented in the literature that financial development drives up the impact of CO₂ emissions through increases in real economic activities and the consumption of polluting fossil fuel energy. However, when dealing with stock market development, such upward effects on economic growth, energy efficiency, and carbon emissions seems to give away to a positive impact especially in emerging markets. This study contributes to this debate by exploring both the symmetric and asymmetric responses of CO₂ emission to changes in stock market development indicators. In particular, using both the panel linear and nonlinear ARDL, our results demonstrate the asymmetric effects of stock market development indicators on carbon emissions in the context of emerging markets. In particular, the long-run elasticities results suggest that positive and negative shocks on stock market indicator decreases environmental quality by increasing carbon emissions. Based on these empirical findings, this study offers some crucial policy implications. Especially, policy makers should implement strong environmental policies in emerging markets economies to reduce carbon emissions of industrial companies without significantly affecting the development of financial markets.

1. This chapter is an article written with co-authors : Stéphane GOUTTE, Mohamed Imen GALLALI, and Khaled GUESMI

3.1 Introduction

It has been variously argued that the rapidly changing climate and environmental degradation is one of the greatest problems facing humanity in recent times. As stated in its 2030 Agenda for Sustainable Development, the United Nations re-demonstrates its commitment and determination to protect the planet from degradation, including through sustainable consumption and production through a sustainable management of the earth's scarce natural resources and taking urgent action on climate change, with the aim of supporting the needs of both the present and future generations (U.N. 2015). Prominent among other factors, carbon dioxide (CO₂) emissions and air pollution stemming from the manufacture and the burning of fossil fuel have been identified as a leading causes of climate change. Consequently, given the damaging effects of climate change on the process of economic growth and financial market development, a growing level of research has been dedicated towards sustainable economic growth and financial market development through reduction in carbon dioxide emission by researchers, financiers, and policymakers.

For instance, an increasing number of empirical studies have investigated the relationship between stock market development, economic growth, and environmental quality for different countries. Results from these studies demonstrate that the development of stock market may exert two opposing impacts on environmental quality across different countries and regions (see e.g. Paramati et al. 2017; Zafar et al. 2019; Zhao and Yang, 2020). Furthermore, another strand of literature has incorporated the roles of conventional and renewable energy consumption in the relationship between stock market development and environmental quality. This trend in literature has been attributed to the perceived role of the current energy mix which is dominated by fossil fuel energy consumption. Moreover, the financial markets in advanced countries are well developed with market participants and policymakers bounded by the strict regulations that control the level of carbon emissions in listed companies by adopting energy efficiency technologies and enhancing the use of green energies in place of conventional energies in order to improve environmental quality.

However, to our best knowledge, there is paucity of empirical studies on the impacts of financial markets on environmental quality across emerging markets. Relative to developed markets, there are remarkable peculiarities that suggest that the effects of stock markets on environmental quality may be asymmetric due to the differences in the level of stock market development between developed and emerging markets. First, emerging markets are defined by market volatility due to political instability, external price movements, as well as supply and demand shocks. These factors exposes investors to risk fluctuation in market performance as well as exchange rates. Further, emerging markets are attractive to foreign investors because of high returns on investment. They are characterized by higher rates of GDP growth, stock prices, and returns for investors due to their competitive advantage notably, in

the export of commodities. Second, in emerging countries, the use of conventional fossil fuel energy remains widespread in the production of most goods and services, making it crucial to explore the determinants of energy demand. More so, the increasing level of economic activities in emerging markets entails rapid increase in energy demand.

Thirdly, given that stock market development is multi-dimensional and has been variously captured using a set of competing indicators, the perceived asymmetry across the effects of these indicators on environmental quality has also attracted the attention of researchers and policy makers (see e.g. Alex et al 2020). Also, many studies have also investigated the non-linearity in the relationship between stock market indicators, energy prices and environmental quality (see e.g. Xu et al 2019; Tuna and Tuna 2019; Balcilar et al 2019; Chkir et al 2020; Escobari and Sharma 2020). Regarding the non-linear effects of financial market development on environmental quality, empirical results have been diverse across different countries. For instance, recent findings from Yue et al (2019) demonstrate that financial development has significant nonlinear effects on energy consumption in transitional countries. In the literature, most studies have investigated the link between financial development and energy demand using the composite stock market development index. However, just a very few studies have explored the asymmetric impact of stock market development on carbon missions especially in emerging markets. In this study, we examined both linear and nonlinear relationship between the development of stock market and environmental quality.

3.1.1 Stock market – environmental quality nexus :

Energy consumption remains a key factor that has led to the recent increases in the level of carbon emissions. Also, stock market development has been indirectly linked to the substantial increase in the consumption of energy in recent times. This is because the activities of stock markets have impact on the quality of the environmental at least in two different ways. On one hand, some studies have highlighted the positive impact of stock market indicators on CO₂ emission. First, stock market development provides new sources of funds, it represents another way through which equity finance can be raised and this can help companies grow and raise further development. In addition, the stock market is considered critical to economic development by giving companies the ability to rapidly access capital from the public which leads to increase in economic activities such as manufacturing activities. Second, economic growth is strongly related to energy consumption, with the growth of business and production activities leading to the consumption of more energy which promotes the increase in carbon emissions (Sadorsky, 2011).

On the other hand, by enforcing strict regulations on listed companies, financial markets have the potential to facilitate an increase in energy efficiency which strengthens environmental quality by reducing carbon emissions.

Previously, conventional energy played a primary role in energy consumption for production, and this use has many disadvantages. This is because primary or conventional energy sources come essentially from fossil fuel. Put differently, this is a non-renewable energy source as it comes from sources that will run out or will not be replenished within a lifetime. Secondly, the use of conventional energy sources can affect environmental quality negatively by increasing carbon emission. However, despite this fact, stock market has the potential to enforce environmental quality by making strong regulations on listed companies (Lanoie et al. 1998).

Furthermore, such regulation may be enforced to control listed companies and to limit their level of conventional energy demand. Consequently, this regulation tends to increase environmental quality by promoting the adoption of energy efficient and greener technologies by listed companies. However, renewable energies can play an important role in reducing carbon emission. In this case, the stock market represents an important source of financing for green investment, making fund more available for clean and renewable energy projects. Taken together, these roles of the financial markets help economies to limit the increasing demand for fossil-fuel energy sources and limit CO₂ emissions, which are associated with environmental quality. The main concern of this study relates to investigating both the symmetric and asymmetric relationship between stock market development, energy consumption, and environmental quality. Thus, this study aims to contribute to the understanding of the role of stock markets, energy consumption in environmental quality.

3.2 Literature review

Given that energy consumption plays a key role in determining the level of environmental quality, through the role of energy use in carbon emission. This section summaries the existing empirical findings and methodologies used in the literature on how economic growth impacts on carbon emission via energy consumption. On the other hand, we focus on the role of the stock market development in energy use and carbon emissions. First, many studies have concentrated on the relationship between energy consumption and economic growth. Most of these studies have identified the causal relationship between energy consumption and economic growth. These studies were driven by the fact that energy resources represent a key factor of production in the sense that energy consumption was considered as a factor influencing economic growth by increasing production (Georgescu-Roegen, 1975).

Fundamentally, some studies have demonstrated that energy consumption is a result of macroeconomic conditions (see e.g. Lermitt and Jollands, 2001). Even more, Bartleet and Gounder (2010) provide an overview of the links between energy consumption and real GDP using trivariate and multivariate models. Their findings supports the presence of causal relationship between energy consumption and real GDP. They also show a long-run causality when energy consumption is the dependent variable and a short run causality from real GDP to total energy

consumption. This provides further support that economic growth causes demand for energy. In addition, Bekaert et al (2001, 2003, 2005) provide analyses of the relationship between financial liberalization, stock market liberalization and economic growth. The results of their study show that financial liberalization is associated with significant increases in real economic growth, especially for emerging markets. Previous researches who focused on environmental quality have investigated the linkages among financial development, economic growth, energy use, and carbon emission. Most of them have relied on Foreign Direct Investment (FDI) as proxy for domestic financial market development because it is widely assumed that economies with high level of financial market development has the potential of attracting more FDI (see e.g. Abbasi and Riaz, 2016).

Using different methods of estimation, many studies have explored the link between FDI and environmental quality (see e.g. Seker et al, 2015; Haug and Ucal, 2019; Demena and Afesorgbor, 2019). Particularly, Muhammad and Shan (2019) have demonstrated that FDI, energy consumption, and carbon emissions play a crucial role in the growth of economic activities in Asian countries. Following this findings, they recommend the use of new policies to promote the transition to clean energy use in order to alleviate environmental pressure from fossil fuel based energy consumption. Moreover, apart from economic growth, financial markets development indexes are among key variables of interest in energy studies. Financial market development can affect energy demand positively, which decreases indirectly environmental quality by increasing CO₂ emissions. While the development of stock market can affect environmental quality in this way, empirical evidence suggest that stock market development can also improve energy efficiency by enhancing the introduction of energy-saving technologies and financing clean energy projects (see e.g. Paramati et al, 2017, Zfar et al 2019 Zhao and Yang 2020).

It is widely held that financial development significantly affects energy consumption. However, whereas many studies have focused on the links between environmental quality and economic development, much attention has not been given to the links between financial development energy demand. Economic theory and many empirical studies have highlighted the importance of capital markets as a major drive of economic development. In a bid to strengthen pollution control, Lanoie et al. (1998) argue that policymakers enforce actions for investors to evaluate and compare companies with regards to their environmental performance. The stock market is considered as an excellent economic indicator of a country's real economic activities; it reflects the financial situation of listed companies and plays a vital role in economic growth. The development of stock market has the potential to attract more investors and expand their business activities (Sadorsky, 2010).

However, despite the clear theoretical links between stock market development and energy demand, the impact of financial development on energy use has attracted a growing attention, especially in recent decades. Whereas most of these studies have concentrated on developed markets, only a few studies have investigated the links bet-

ween stock market development and energy consumption in emerging economies. The development of stock market activity induces economic growth and this impacts the demand for energy because economic growth requires more energy consumption. In particular, Sadorsky (2010) using key stock market indicators found that the development of stock market has a significant positive impact on energy consumption in 22 emerging economies. In a similar study, Sadorsky (2011) examined the impact of financial development on energy consumption for nine countries of Eastern and central Europe frontier economies using panel Generalized Method of Moments (GMM). The results suggest that only stock market turnover has a positive and significant impact on energy consumption.

A growing stream of empirical studies have focused on the role of stock market development in environmental quality. For instance, Shahbaz et al. (2013) investigated the linkage between economic growth, energy demand, financial development, and carbon emissions in Indonesia, using the ARDL method. The results of this study indicated that economic growth decreases carbon emission while financial development decreases it. Moreover, the result obtained by the VECM test found that exists bidirectional causality between economic growth and CO₂ emission ; likewise, financial development granger causes carbon emission, knowing that financial development was proxied by real domestic credit to private sector per capita. Chang (2015) investigated nonlinear effects of financial development and income on energy demand using a panel threshold approach, he finds that energy use increases with economic growth in emerging market and developing economies while energy consumption increases with economic growth at a turning point which the economy achieves a threshold level of income in advanced economies.

Furthermore, in a more recent empirical study, Ulusoy and Demiralay (2016) focused on the impact of stock market developments on oil and electricity demand of OECD member countries using the Partial Adjustment Model (PAM) the results suggest that stock market development indicators affect positively and significantly both oil and electricity consumption. Lin and Benjamin (2018) have also examined the interactions between economic growth, energy consumption and foreign direct investment using a panel dynamic ordinary least squares model, the result reveals that there exist a bi-directional causal relationship between economic growth and energy consumption in a global panel. In the same vein, Gaies et al (2019) examined the link between financial development and energy consumption in several MENA countries, the results of linear and non-linear dynamic panel models indicate a non-linear and inverted U-shaped relationship between financial development and energy demand. This study supports the view that energy consumption is initially positively related to financial development and it declines at a turning point of financial development.

Moreover, Yue et al (2019) demonstrate that the development of stock market leads to a decrease energy consumption especially in developed stock markets due to decreasing financing costs for public and private sectors which helps to introduce advanced energy-saving technologies and improve energy efficiencies. Moreover, Apergis

and Gangopadhyay (2020) have tested the asymmetric relationship between pollution and energy consumption in Vietnam using the NARDL method. Recent studies have focused on the role of stock market development on renewable energy use. Strong stock markets where investors enhance listed companies to use renewable energy in order to maintain energy efficiency and increase environmental quality Paramati et al (2017). Using Auto-Regressive Distributed Lag ARDL method, Ramzi et al (2019) have examined the relationship between two types of renewable energy consumption, stock market development and economic growth in Iran, the results show that stock market value impacts, in the long-run, renewable energies consumption.

In addition, Fan and Hao (2019) have found a causal relationship between renewable energy consumption, economic growth, and foreign direct investment. Contrariwise, Tuna and Tuna (2019) have found that there is a non-causal relationship between economic growth and non-renewable energy consumption for major countries of ASEAN-5 countries. Ziaei (2015) investigated the effects of credit market and stock market shocks on energy consumption and CO₂ emissions in European, East Asian and Oceania countries. The result indicates that stock variables have an important effect on energy consumption in countries with developing asset markets. Begum et al (2015) find that per capita energy consumption and per capita GDP have a long-term positive effect on per capita carbon emissions. Many studies have highlighted the role of renewable energy use in the maintenance of environmental quality. (Salim and Rafiq, 2012) have found that renewable energy consumption is determined by both income and carbon emissions in a number of emerging market economies. In addition, the finding of (Bahattacharya et al, 2016) shows that renewable energy use has a positive and significant effect on economic growth in 38 of major economies.

Stock market development is taking place between the most vital sources of financing clean energy project, which lead to a higher level of investment in clean energy project (Sadorsky 2010, 2012; Alam et al., 2015; Paramati et al 2016; Paramati et al 2017). Several studies suggest that stock market development play a crucial role in increasing environmental quality by enhancing investment in a clean energy project. The finding of (Paramati et al, 2016) have underlying that both FDI and stock market development have a significant and positive impact on clean energy use in emerging market economies. Considering the fluctuating and highly volatile behavior of a financial component as a stock market, two types of approach have noticed in the literature dedicated to the relationship between stock market and carbon emission. The first approach is a linear method according to which the relationship between these two components would be symmetrical. The second approach is a non-linear approach, which considers that the increases and decreases of the stock market variable would have rather asymmetrical implications on CO₂ emission.

Lastly, many studies have explored the asymmetric relationship between stock market, energy price and economic growth using various econometric methods. Several studies have investigated the link between the oil price

shocks and various economic variables using nonlinear approaches Zhang (2008) ; Nusair (2016). Recently, Khan et al (2020) have examined the asymmetric effect of energy use and economic growth on environmental quality using NARDL technique ; the findings ascertain the asymmetric effect between positive shocks to environmental quality and energy consumption. Moreover, many studies have explored the asymmetric relationship between energy use and stock market and environmental variables. Apergis and Gang (2020) tested the presence of asymmetric relationships between pollution, energy use and oil prices in Vietnam using a Non-linear Auto-Regressive Distributed Lag (NARDL) model. The result suggest that In addition, using the same method, Qamruzzaman and Jianguo (2020) confirmed the presence of an asymmetric relationship between financial development, foreign capital flows, trade openness, and renewable energy consumption.

3.3 Data and methodology

3.3.1 Data

In this study, we use a panel data comprising 19 emerging markets. In particular, the selected emerging markets includes Brazil, Chile, China, Colombia, Czech Republic, Greece, Hungary, India, Indonesia, Korea, Malaysia, Mexico, Pakistan, Peru, Philippines, Poland, South Africa, Thailand, and Turkey. Our dataset is a balanced yearly panel data that covers the period from 1994 to 2014. Following the usual procedure, we converted all variables into their natural logarithmic equivalents before proceeding with the estimation. Consequently, this enables us to estimate coefficients that are interpreted as the elasticities following numerous previous studies (Battacharya et al 2017, Paramati et al 2016 ; 2017).

In Table 3.1, we present the definition of all the variables used in this study as well as their sources while Table 3.2 displays the descriptive statistics of all the variables for each emerging market economy for the period from 1995 to 2014. From Table 3.2, we can deduce that there is a significant difference in per capita carbon emissions across these economies. In particular, Czech Republic has the highest carbo emission of about 11.24 metric tons followed by Korea with about 9.99 metric tons are the two most carbon emitting economies while Philippines with about 0.89 metric tons followed by Pakistan 0.817 metric tons are the least. Further, energy intensity appear to be highest in South Africa (10.15 MJ/\$) and in China (9.97 MJ/\$), whereas the lowest is in Colombia (2.92 MJ/\$) and in Peru (2.74 MJ/\$). The Highest per capita market capitalization are achieved in China (2.49e+12\$) and India (9.93e+11\$), while the lowest stock market capitalization are in Czech Republic (2.73e+10\$) and Hungary (2.63e+10\$). Likewise, Korea (19393.35 \$), Greece (4697.7 \$) and Turkey (2801.777 \$).

The correlation matrix is a primary step towards establishing the nature of the relationship between the set of variables. Table 3.3 presents the correlation matrix of the variables used in this study. As noted in Kevin (1992),

TABLE 3.1 – Variables definitions

	Variables	Definition	Sources
Environmental quality	CO2 emission per capita	The per capita metric ton carbon dioxide emission	WDI
Stock market development indicators	Stock market capitalization per capita	Total market capitalization of listed domestic companies as current USD Divided by the total population of the country,	WDI
Stock market development indicators	Stock traded per capita	Stock traded total value as current USD divided by total population.	WDI
Economic output	GDP per capita	The per capita gross domestic product.	WDI
Population	Population density	People per sq. km of land area	WDI
Energy consumption	Energy intensity	Energy intensity level of primary energy calculated as units of energy per unit of GDP.	WDI

the likelihood of the presence of the problem of multicollinearity becomes high when the correlation coefficient between dependent and independent variables exceeds 0.7. As may be seen in Table 3.3, the coefficient of correlation between stock market development indicators and carbon emissions per capita (*CEPC*) do not exceed 0.7, which suggests the absence of multicollinearity problem. However, the correlation coefficient between *GDPPC* and *CEPC* is 0.72; this indicates that these two variables are strongly positively correlated. High economic growth is strongly related to more carbon emission in emerging market economies.

TABLE 3.2 – Summary statistics on individual and panel data set from 1995 to 2014

Country	CEPC	EI	SMPC	STPC	GDPPC	PDPC
Brazil	1.972	3.920	6.28e+11	1941.1	9873.4	22.014
Chile	3.961	4.282	1.51e+11	1334.9	11134.9	21.652
China	4.6316	9.9732	2.49e+12	2373.2	3073.93	137.88
Colombia	1.5681	2.9293	1.46e+11	241.72	5697.1	37.941
Czech Republic	11.243	7.2635	2.73e+10	1495.0	17283.9	133.76
Greece	8.0291	3.8785	1.11e+11	4697.7	24829.3	84.615
Hungary	5.3773	5.3614	2.63e+10	2046.3	11961.2	112.39
India	1.1669	6.2035	9.93e+11	640.83	1066.7	381.95
Indonesia	1.5902	4.5757	1.59e+11	209.87	2668.1	124.35
Korea	9.9963	7.3865	5.95e+11	19393.4	18177.1	496.56
Malaysia	6.5529	5.3495	2.50e+11	2798.8	8004.5	77.262
Mexico	4.1293	4.2658	2.61e+11	650.9	9127.4	54.366
Pakistan	0.8176	5.1739	2.95e+10	247.80	910.54	206.21
Peru	1.3694	2.7445	4.11e+10	115.22	4123.5	21.511
Philippines	0.8961	4.0880	8.80e+10	197.82	1863.2	285.9
Poland	8.1815	6.316	9.22e+10	925.76	10205.5	124.93
South Africa	8.9092	10.159	5.14e+11	2674.6	6632	39.379
Thailand	3.5805	5.3209	1.58e+11	1747.5	4307.8	126.67
Turkey	3.6542	3.6615	1.38e+11	2801.7	9610.4	87.648
Consolidated						
Observation	380	380	380	380	380	380
Mean	4.6119	5.4134	3.63e+11	2449.2	8450.0	135.63
Maximum	12.365	14.228	6.00e+12	39394.9	30054.9	520.85
Minimum	0.68255	2.3419	4.56e+09	2.7633	674.62	18.983
Std. dev	3.3149	2.1629	7.23e+11	5217.6	6450.1	124.87

Note : CEPC : Per capita CO2 emissions in metric tons ; EI : Energy intensity level of primary energy (MJ/\$2011 PPP GDP) ; SMPC : Market capitalization of listed domestic companies (current US\$)/total population ; STPC : Stocks traded, total value (current US\$)/total population ; GDPPC : GDP per capita (constant 2010 US\$) ; PDPC : Population density (people per sq. km of land area)

TABLE 3.3 – correlation matrix

	CEPC	EI	SMCPC	STPC	GDPPC	PDPC
CEPC	1.000					
EI	0.502	1.000				
SMCPC	0.055	0.347	1.000			
STPC	0.475	0.159	0.229	1.000		
GDPPC	0.724	-0.059	-0.113	0.508	1.000	
PDPC	0.092	0.246	0.173	0.492	-0.012	1.000

Figures 1 to 6 present the evolution by country of per capita CO2 emissions, energy intensity, stock market development indicators, GDP per capita, and population density per capita.

Figure 1 shows the evolution of emissions between 1994 and 2014 by country. At first sight, we notice a strong increase in the share of CO2 emissions in China, the Czech Republic, Korea, South Africa, Greece, and Poland, which is accompanied by a high level of energy intensity. This evolution is linked to the economic development of these countries whose share of GDP in the world GDP has increased from 27,4% in 1992 to over 40% in 2011 according to World Bank. In addition, foreign direct investment, especially in the manufacturing and services sectors of emerging countries, has contributed to their rapid growth.

For Greece, CO₂ emissions per capita have increased sharply since the 1990s and are higher than the OECD-Europe average. Lately, Greece is on track to meet the Kyoto Protocol target of limiting the increase in emissions. For the Czech Republic, there has been a slight decrease in emissions since 2010. despite the high level of pollution and increased growth in energy intensity (figure 2), Czech has developed an integrated energy-climate plan to achieve GHG reduction targets by 2030 and 2050 to strengthen the political commitment to a low-carbon economy.

Energy consumption and economic development have been decoupled from gross domestic product (GDP). As world GDP increased sharply between 1990 and 2018, while total energy supply increased by 59%, the amount of energy intensity, decreased overall by 36% between 1990 and 2018 according to the IEA. Figure 2 shows a regional variation of emerging countries. In China, the decline was more significant. China's energy intensity falling by more than half over this period.

Figures 5 and 6 present the evolution of the two indicators of financial market development by country. The presence of a fluctuating aspect for these two variables can be seen, in other words, these variables can also have a non-linear impact, which leads us to make a non-linear analysis of the relationship between financial market development and environmental quality.

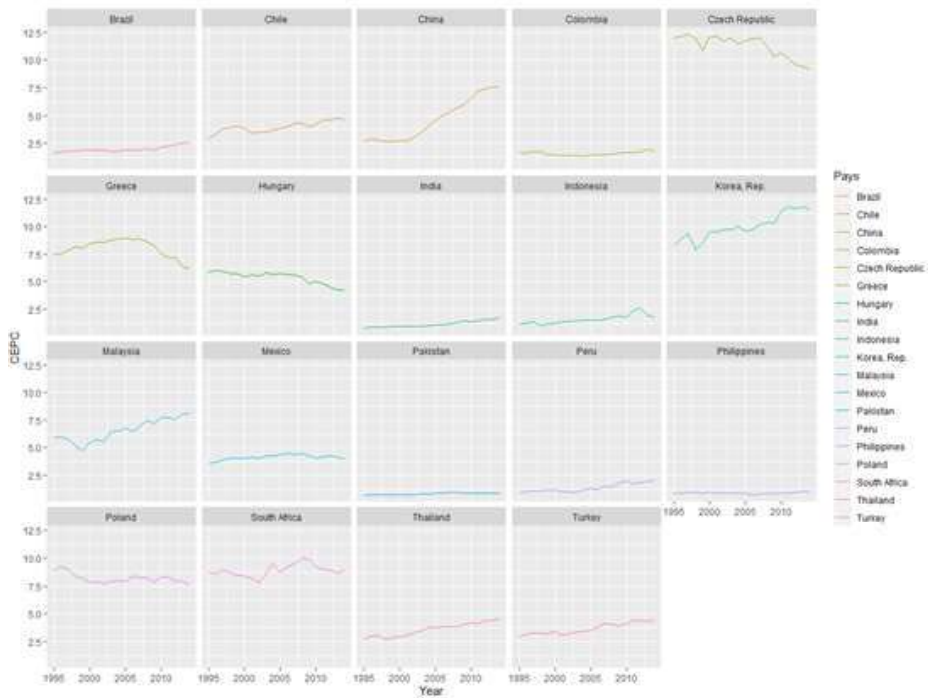


FIGURE 3.1 – Plot of carbon emission per capita

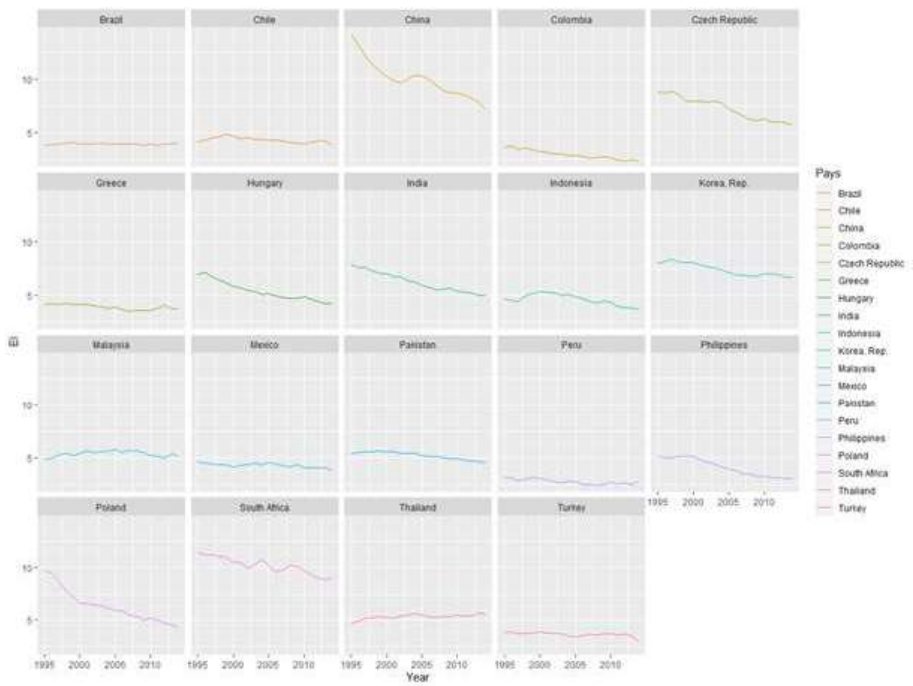


FIGURE 3.2 – Plot of energy intensity

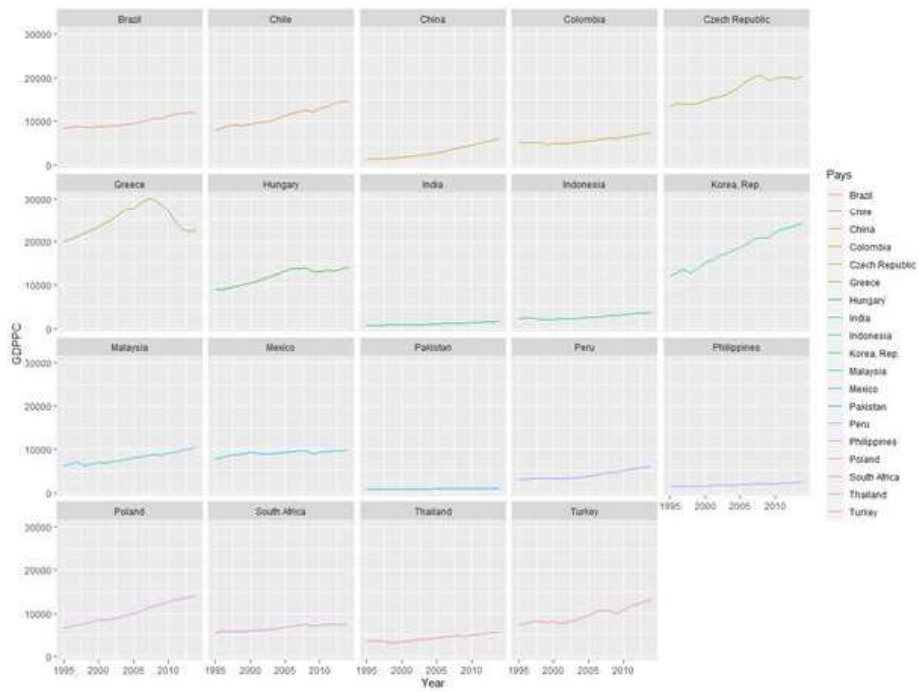


FIGURE 3.3 – Plot of GDP per capita

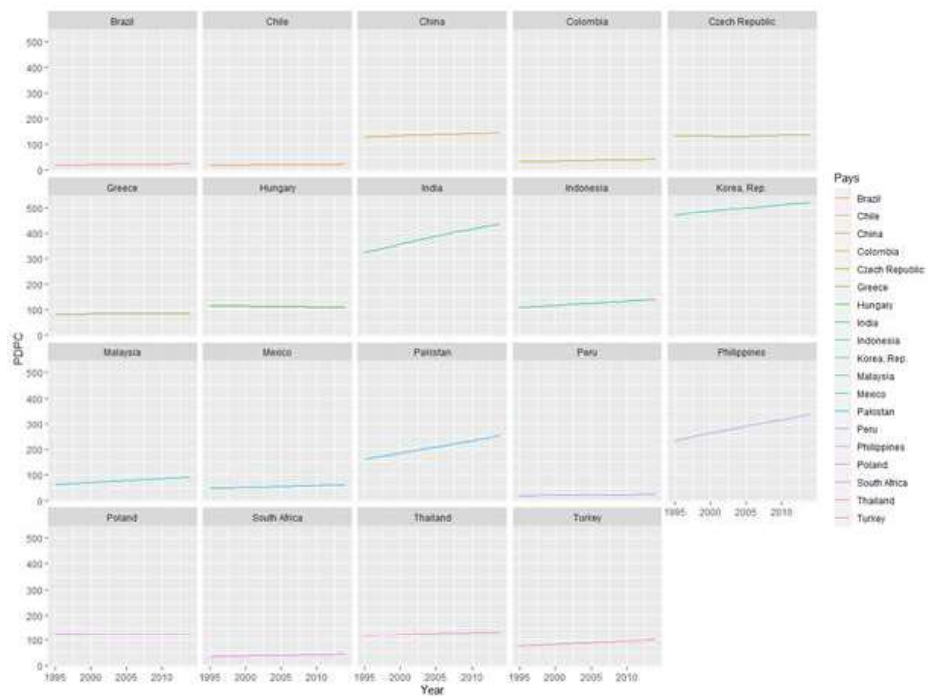


FIGURE 3.4 – Plot of population density per capita

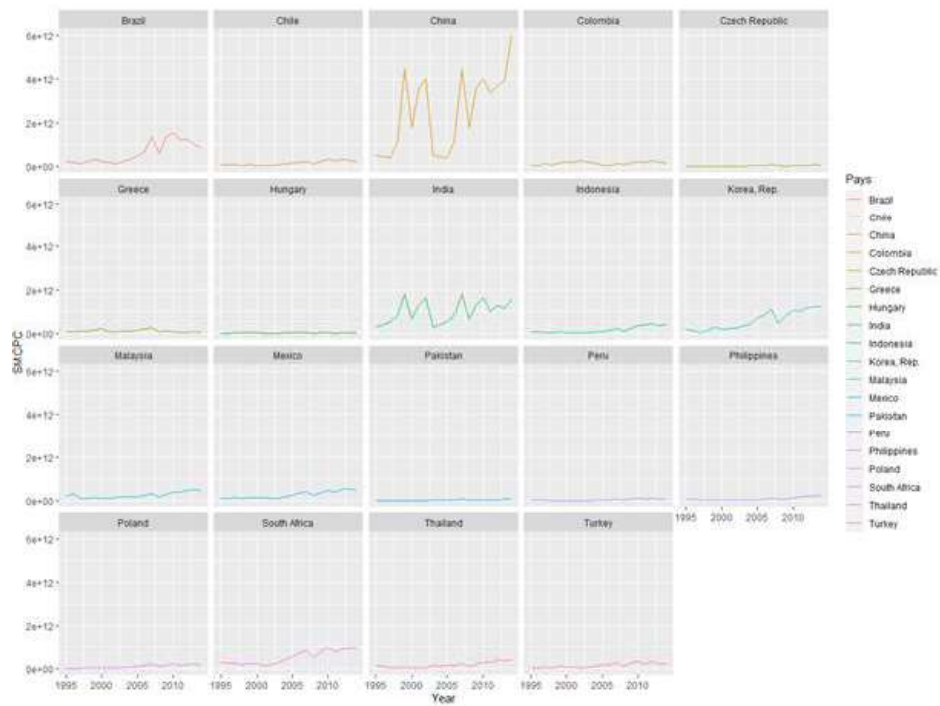


FIGURE 3.5 – Plot of stock market capitalization per capita

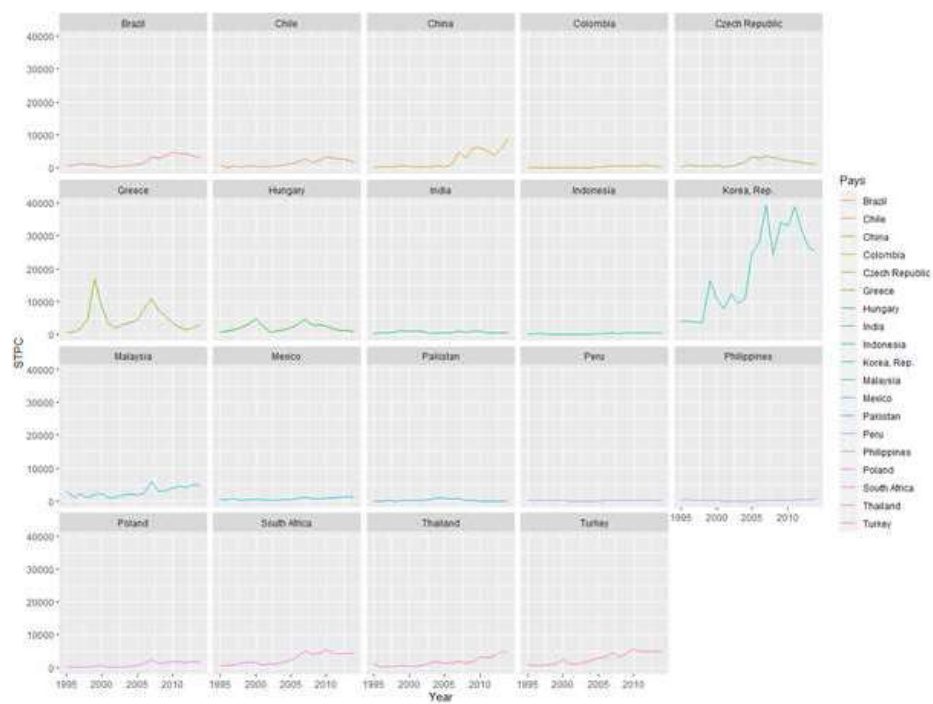


FIGURE 3.6 – Plot of stock traded per capita

TABLE 3.4 – Panel unit root tests results

Method	Levin-Lin-Chu		Im-Pesaran-Shin		ADF		PP		Harris-Tzavalis	
	Level	1st diff.	Level	1st diff.	Level	1st diff.	Level	1st diff.	Level	1st diff.
lnCEPC	1.194	-6.525***	4.235	-7.184***	18.44	299.1***	18.44	299.1***	0.951	-0.068***
lnEI	-1.109	-5.681**	2.263	-6.706***	24.09	141.4***	31.89	272.6***	0.949	-0.002***
lnSMCPC	-1.723	-12.54***	0.511	-10.99***	33.72	268.2***	38.09	372.8***	0.789*	-0.165***
lnSTPC	-2.513**	-5.520***	-0.143	-6.966***	42.21	148.6***	32.16	387.2***	0.832	-0.019***
lnGDPPC	0.413	-5.485***	5.819	-5.301***	14.43	115.1***	14.7768	170.0***	0.999	0.223***
lnPDPC	3.089	-10.52***	6.466	-7.434***	24.17	210.3***	673.2***	106.3***	0.977	0.818

Note : *, **, and *** denote significance at 10%, 5% and 1% respectively.

The linear and non-linear ARDL methodology of cointegration is appropriate because it does not require that variables included in the model are I (0) or I (1). In order to ascertain the absence of I (2) variables in the model, it is mandatory to apply stationarity tests. We started our empirical analyses by examining the integration properties of all variables using four unit root tests as of Levin, Lin, and Chu (2002), a similar test is described by Harris and Tzavalis (1999), the Im, Pesaran, and Shin (2003) test, Fisher type test based on Dickey-Fuller and Philips-Perron. Table 3 show the results of unit root tests, which indicate the presence of unit root problems at level, but all underlying data becomes stationary at first difference for all variables.

3.3.2 Model specification

As mentioned in the previous section, the main objective of this study is to examine both the symmetric and asymmetric relationship between stock market development, energy consumption and environmental quality. To accomplish this objective, we rely on the IPAT environmental model that was first proposed by (Ehrlich and Holdren, 1971). The fundamental form of the IPAT model may be described as follows :

$$I = PAT \quad (3.1)$$

Where I , P , A , and T represent environmental quality or pollution, population, Affluence lever of a region, technology, or development level, respectively. Recently, the IPAT model has been extended by Dietz and Rosa (1994, 1997) in order to obtain a stochastic version. The new version is known as STIRPAT model (Stochastic impact by regression on population, affluence, and technology model). The STIRPAT model explains environmental quality in terms of three important determinants of CO₂ emissions as population, economic output, and technology level in the country.

The variant of this model that we adopted for this study may be represented as follows :

$$\ln I = \alpha + \beta \ln P + \delta \ln A + \lambda \ln T + \gamma \ln S + \varepsilon \quad (3.2)$$

where I represents per capita carbon emissions (metric ton per capita), P represents population density (people per sq.km of land area). A denotes affluence represents GDP per capita, T explains energy intensity level of primary (quantity of energy required per unit of output), and S represents stock market development measures (stock market capitalization and stock traded). As mentioned above, we developed a model using two different measures of stock market development (stock market capitalization and stock traded) following the study of Paramati et al (2018).

The functional form of Equation 6.16 may be written as follows :

$$\ln CEPC_i = \beta_0 + \beta_1 \ln EI_{i,t} + \beta_2 \ln SMD_{i,t} + \beta_3 \ln GDPPC_{i,t} + \beta_4 \ln PDPC_{i,t} + \varepsilon_{i,t} \quad (3.3)$$

Where *CEPC* represents per capita carbon emission, *EI* represents energy intensity, *SMD* is a stock market development indicators (*SMCPC* means a per capita stock market capitalization and *STPC* is a stock traded per capita), *GDPPC* is a per capita gross domestic product, *PDPC* represents population density per capita, and β_i represents the long-run coefficients vectors. In the next sections, we develop this model into linear and nonlinear forms using ARDL and NARDL methodologies.

The symmetric panel ARDL

In this study, we are first interested in the symmetric response of stock market development to environmental quality. To achieve this particular aim, we apply the Auto-Regressive Distributed Lag model (ARDL) proposed by (Pesaran and Shin, 1998). This model enables us to estimate the cointegration relationship among stock market development indicators, energy use and carbon emission. The ARDL model may be stated as follows :

$$\Delta y_t = \sum_{i=1}^n \beta_i \Delta y_{t-i} + \sum_{i=0}^n \delta_i \Delta x_{t+i} + \phi_1 \Delta y_{t-1} + \phi_2 \Delta x_{t-1} + \mu_t \quad (3.4)$$

Based on the objective of this study which is to investigate the relationship between per capita stock market development variables, energy use, economic output, population density and per capita carbon emissions, the above ARDL model to modified as follows :

$$\begin{aligned} \Delta \ln CEPC = & \beta_0 + \alpha_1 CEPC_{t-1} + \alpha_2 EI_{t-1} + \alpha_3 SMD_{t-1} + \alpha_4 GDPPC_{t-1} + \alpha_5 PDPC_{t-1} \\ & + \sum_{j=0}^p \beta_{1i} \Delta EI_{it-j} + \sum_{j=0}^p \beta_{2i} \Delta SMD_{it-j} + \sum_{j=0}^p \beta_{3i} \Delta GDPPC_{it-j} + \sum_{j=0}^p \beta_{4i} \Delta PDPC_{it-j} + \epsilon_{it} \end{aligned} \quad (3.5)$$

Where, $\sum_{j=0}^p \beta_{1i}$ represents the short-run effect of Stock market development on carbon emission while α_3 represents the long run effect of Stock market development on carbon emission. The error correction model of the above equation is represented as follow :

$$\begin{aligned} \Delta \ln CEPC = & \beta_0 + \sum_{j=0}^p \beta_{1i} \Delta EI_{it-j} + \sum_{j=0}^p \beta_{2i} \Delta SMD_{it-j} \\ & + \sum_{j=0}^p \beta_{3i} \Delta GDPPC_{it-j} + \sum_{j=0}^p \beta_{4i} \Delta PDPC_{it-j} + \theta_i ECT(t-1) + \epsilon_{it} \end{aligned} \quad (3.6)$$

where θ_i denotes the long-run equilibrium speed of adjustment after the shock in the short-run.

The asymmetric panel ARDL

Several empirical studies have demonstrated the presence of asymmetries in the impact of stock market indicators on different dependent variables. In other words, positive and negative shocks on stock market indicators appear to have asymmetric effects on other variables. To investigate the presence of this phenomenon on the effects of stock market development indicators on carbon emissions, we rely on the Non-linear ARDL (NARDL) approach which allow us to examine both short- and long-run asymmetric responses of carbon emission to positive and negative shocks on stock market development. To examine this nonlinear relationship, we decompose changes in the exogenous variable (stock market development) into its positive and negative partial sums of increases and decreases, to examine their impact on the independent variable (CO₂ emission per capita).

Following the above, we rely on NARDL model proposed by Shin et al (2014). The NARDL may be stated as follows :

$$\begin{aligned} \Delta \ln CEPC = & \gamma_0 + \vartheta_1 \ln CEPC_{t-1} + \vartheta_2 \ln EI_{t-1} + \vartheta_3 \ln SMD_{t-1}^+ + \vartheta_4 \ln SMD_{t-1}^- \\ & + \vartheta_5 \ln GDPPC_{t-1} + \vartheta_6 \ln PDPC_{t-1} + \sum_{j=0}^p \delta_{1i} \Delta \ln EI_{it-j} + \sum_{j=0}^p \delta_{2i} \Delta \ln SMD_{it-j}^+ \\ & + \sum_{j=0}^p \delta_{3i} \Delta \ln SMD_{it-j}^- + \sum_{j=0}^p \delta_{4i} \Delta \ln GDPPC_{it-j} + \sum_{j=0}^p \delta_{5i} \Delta \ln PDPC_{it-j} + \epsilon_{it} \end{aligned} \quad (3.7)$$

where, $\sum_{j=0}^p \delta_{2i}$ and $\sum_{j=0}^p \delta_{3i}$ captures the short-run positive and negative effect of Stock market development on environmental quality while ϑ_3 and ϑ_4 captures the long-run effect stock market growth on carbon emission. Lastly, the error correction equation may be represented as follows :

$$\begin{aligned} \Delta \ln CEPC = & \gamma_0 + \sum_{j=0}^p \delta_{1i} \Delta \ln EI_{it-j} + \sum_{j=0}^p \delta_{2i} \Delta \ln SMD_{it-j}^+ + \sum_{j=0}^p \delta_{3i} \Delta \ln SMD_{it-j}^- \\ & + \sum_{j=0}^p \delta_{4i} \Delta \ln GDPPC_{it-j} + \sum_{j=0}^p \delta_{5i} \Delta \ln PDPC_{it-j} + \rho_i ECT_{t-1} + \epsilon_{it} \end{aligned} \quad (3.8)$$

3.3.3 Empirical results and discussion

In this section, we present results from our analysis of the linear and nonlinear relationship between stock market development, energy use and carbon emission across the panel of 19 chosen emerging market economies. The discussion of these analyses are presented in the following subsections.

Results from panel ARDL model

In this section, we investigate both the short-run and the long-run linear impact, respectively, of stock market development indicators and energy efficiency on carbon emission across the panel of emerging market economies. As stated earlier, we transformed all the variables into their natural logarithms in order to interpret the estimated coefficients as elasticities. Table 3.5 presents the short- and long-run linear relationship as defined in Equation 3.5. As may be seen in Table 3.5, the short-run elasticities suggest that energy intensity has a positive and significant effect on carbon emission at the 1% level. This suggests that a 1% increase in energy use raises CO₂ emission by 0.53%. In addition, economic growth has a positive and significant impact with about 0.6% rise in carbon emission being explained by a 1% growth in GDP per capita. Regarding stock market indicators, the stock market capitalization appear not to be statistically significant while the volume of stock traded is negative but significant only at 10% level. Moreover, the long-run estimation results suggest that energy intensity has a significant and positive impact of about 0.8% improvement in carbon emission being explained by 1% improvement in energy use per unit of GDP. However, population density has a negative and significant impact in the long run at a 1% level, with a two-and-a-half-year adjustment range. Put differently, a 1% raise in per capita population density decreases per capita CO₂ emission by 2.14% and 0.68%.

For stock market development indicators, the results of the linear long-run relationship have significant policy implications. Stock market capitalization becomes significant at a 1% level across all panel in the long-run. This implies that a 1% increase in stock market capitalization increases emissions by 0.02%. Similarly, the long-run elasticities show that a 1% raise in stock traded increases CO₂ emissions by 0.015%. These results are in the line with previous studies such as Paramati et al (2017) and Zafar et al (2019) for emerging market countries. These findings show that stock market development has a negative impact on environmental quality in emerging market economies. This may be explained by the link between financial development, economic growth, energy use and carbon emissions. Financial development is generally accompanied by increased energy consumption and economic growth that contribute to carbon emissions because creating new sources of funds allows firms to extend their production, which contributes to energy use especially fossil fuel energy (see e.g. Lee and Chang, 2008 ; Sadorsky, 2010 ; Warr and Ayres, 2010 ; Ozturk,2010). Lastly, these observed negative relationships between stock market development indicators and environmental quality suggest that emerging market economies should

implement environmentally-friendly policies to reduce carbon emission by maximizing their energy efficiency level.

TABLE 3.5 – Linear ARDL estimations

Variable	Model 1	Variable	Model 2
ECT	-0.377*** (0.081)	ECT	-0.423*** (0.079)
Short run relationship			
D.lnEI	0.532*** (0.136)	D.lnEI	0.525*** (0.141)
D.lnSMCPC	-0.002 (0.008)	D.lnSTPC	-0.009* (0.005)
D.lnGDPPC	0.602*** (0.146)	D.lnGDPPC	0.643*** (0.141)
D.lnPDPC	-2.148 (2.998)	D.lnPDPC	-0.687 (3.125)
Long run relationship			
lnEI	0.809*** (0.112)	lnEI	0.740*** (0.102)
lnSMCPC	0.028*** (0.008)	lnSTPC	0.0145** (0.006)
lnGDPPC	1.285*** (0.643)	lnGDPPC	1.205*** (0.0587)
lnPDPC	-0.929*** (0.155)	lnPDPC	-0.777*** (0.132)
c	-1.184*** (0.282)	c	-1.289*** (0.265)
Obs.	361	Obs.	361

Note : Number in parenthesis indicate standard errors. “***”, “**” and “*” indicate respectively significant value at 1%, 5% and 10%.

Analyses of nonlinear relationship :

Given that this study also aims to deepen the understanding of the asymmetric effects of stock market development in the level of environmental quality. To achieve this goal, we investigate the nonlinear relationship between stock market development indicators, energy efficiency and environment quality using the Nonlinear Auto-Regressive Distributed Lags (NARDL) approach. Table 3.6 reports the estimates from the nonlinear effects of stock market development on environmental quality across our chosen emerging market economies. As may be seen in Table 3.6, the short- and long-run elasticities suggest that energy intensity and economic growth have positive and significant relationship with carbon emissions at 1% level. In particular, about 0.53% increase in carbon emissions is due to a 1% raise in energy use. Also, population density has a significant negative impact on CO₂ emission only in the long run. Specifically, results suggest that a 1% increase in PDPC decrease carbon emissions by 0.7%. Taken together, the nonlinear results suggest that stock market development indicators have a diverse relationship with environmental quality, implying that the development of stock market have an asymmetric impact on environmental degradation in emerging market economies.

Moreover, the volume of stock traded per capita which reflects the level of liquidity in the stock market has a

nonlinear impact on environmental quality. The short-run elasticities suggests that only positive shock has a negative and significant effect on emissions. This implies that a 1% evolution in STPC positive shock decreases carbon emission by 0.02% while in the long-run, a shock on STPC has a positive and significant impact at a 1% level on carbon emission. Also, the relationship between the positive and negative partial-sums of stock market capitalization and carbon emissions show that positive shocks in stock market have no significant impact on emissions in the short-run, while ; negative shocks have a negative and significant impact on CO₂ emission at a 10% level. Although, the long-run elasticities show both SMPC positive and negative shocks have a positive and very significant impact on environmental degradation. In other words, 1% evolution in positive and negative shocks of stock market capitalization increase respectively carbon emissions by 0.023% and 0.042%. Lastly, these outcomes suggest that negative shocks on stock market capitalization has a greater impact on carbon emissions. A possible explanation to this is that when stock market capitalization increases, there seem to be fewer opportunities to finance green project and new technologies and thus, there will be recourse to the use of polluting fossil fuels.

Panel granger causality results

In this subsection, use Granger causality tests to identify the predictive power of a variable X for variable Y. We say X granger causes Y, if the past information in variable X yields better forecasts of Y. In other words, if variable X granger causes variable Y, repeated changes are observed in series Y after the changes in series X, approximately. Indeed, compared to times series models, panel data models present some advantages for causal relationship test, because ; first, they include more observations than individual time series. Second, they allow for modelling the cross-sectional behavior. In this study, we used Panel Granger causality technique to detect the predictability power that exists among the variables. To develop the policy implications, it is essential to know the two ways causal relationships between variables. In this way, we employ, in this study panel heterogeneous causality method provided by Dumitrescu and hurlin (2012). The related results are presented in Table 3.7. As we can notice in Table 3.7, the Granger causality results indicate that bidirectional causality runs between energy intensity, economic growth, population density and carbon emissions. Put differently, the connection between stock market development indicators and carbon emission is bidirectional, which is in the line with Zafar et al (2019). Meanwhile, the outcomes of nonlinear causality show that only negative changes in per capita stock market capitalization have a predictive power on CO₂ emissions. This indicates that there exists an asymmetric causality relationship between stock market development and carbon emission.

TABLE 3.6 – Nonlinear ARDL estimations

Variables	Model 1	Variables	Model 2
ECT	-0.381*** (0.081)	ECT	-0.447*** (0.099)
Short run relationship			
D.lnEI	0.509*** (0.142)	D.lnEI	0.500*** (0.154)
D.lnSMCPC ⁺	0.013 (0.019)	D.lnSTPC ⁺	-0.020* (0.011)
D.lnSMCPC ⁻	-0.017* (0.009)	D.lnSTPC ⁻	0.001 (0.007)
D.lnGDPPC	0.604*** (0.146)	D.lnGDPPC	0.618*** (0.149)
D.lnPDPC	-1.626 (3.026)	D.lnPDPC	0.178 (3.409)
Long run relationship			
lnEI	0.918*** (0.120)	lnEI	0.784*** (0.079)
lnSMCPC ⁺	0.024** (0.013)	lnSTPC ⁺	0.036*** (0.009)
lnSMCPC ⁻	0.043*** (0.012)	lnSTPC ⁻	0.012 (0.010)
lnGDPPC	1.288*** (0.075)	lnGDPPC	1.001*** (0.057)
lnPDPC	-0.667*** (0.229)	lnPDPC	-0.761*** (0.177)
<i>c</i>	-1.396*** (0.319)	<i>c</i>	-1.073*** (0.261)
Obs.	361	Obs.	361

Notes : Number in parenthesis indicate standard errors. ***, ** and * indicate respectively significant value at 1%, 5% and 10%.

TABLE 3.7 – Panel granger causality results

Null Hypothesis	<i>W</i> -stat.	<i>p</i> -value	Causality flow
EI → CEPC	2.916***	(0.0035)	EI ↔ CEPC
CEPC → EI	7.286***	(0.0000)	
SMPC → CEPC	3.269***	(0.0011)	SMPC ↔ CEPC
CEPC → SMPC	10.70***	(0.0000)	
STPC → CEPC	7.594***	(0.0000)	STPC ↔ CEPC
CEPC → STPC	5.538***	(0.0000)	
GDPPC → CEPC	5.074***	(0.0000)	GDPPC ↔ CEPC
CEPC → GDPPC	8.6676***	(0.0000)	
PDPC → CEPC	32.26***	(0.0000)	PDPC ↔ CEPC
PDPC → GDPPC	8.114***	(0.0000)	
SMPC ⁺ → CEPC	-0.4385	(0.6610)	SMPC ⁺ ≠ CEPC
SMPC ⁻ → CEPC	3.9095***	(0.0001)	SMPC ⁻ → CEPC
STPC ⁺ → CEPC	3.7275***	(0.0002)	STPC ⁺ → CEPC
STPC ⁻ → CEPC	2.8982**	(0.0038)	STPC ⁻ → CEPC

Note : *** significant value at 1%; ** significant value at 5%; * significant value at 10%.

3.4 Robustness check

In this section we perform a robustness test to verify the robustness of our analyses of the results. First, it is widely known that the ARDL model and especially the panel ARDL model gives a consistent estimator of the best linear predictor irrespective of any assumption about normality. Second, normality in the ARDL model is not a big issue, because even if normality is solved, the results do not change that much. This section aims to demonstrate the robustness of our analysis by a second regression after correction of non-normality of residuals.

The skewness and Kurtosis tests statistic based on the p-value of the joint test shows that the error terms of the models specified in eq(3) should have a non-normal distribution (Table 8). Based on the assumption of regression analysis of skewness and Kurtosis test we reject H0 of normality.

We proceeded to the Box-Cox transformation of the variables to correct the non-normality of the residuals. Box-Cox transformation is a popular approach to adapt data to a linear regression model. The transformation is named after statisticians Georges Box and David Roxbee Cox, who collaborated and developed the technique on a 1964 paper.

A Box-Cox transformation transforms non-normal variables into a normal shape. Normality of residuals is a significant assumption for the robustness of results; if your data isn't normal, applying a Box-Cox means that you are able to run a regression. lambda exponent (λ) is at the heart of the Box-cox transformation. This exponent has a value between -5 and 5 . All values of (λ) are integrated and the optimal value for the data is selected. The "optimal value" is the one that gives the best approximation of a normal distribution curve. Thus, the transformation of Y has the form :

$$y(\lambda) = \begin{cases} \frac{y^\lambda - 1}{\lambda}, & \text{if } \lambda \neq 0 \\ \log(y), & \text{if } \lambda = 0 \end{cases} \quad (3.9)$$

As the Box-Cox transformation is still monotonic, the original order of the data is unchanged after the transformation. Therefore, statistical tests based on ranks will not be affected by this transformation. In the case where $\lambda = 0$ we find our previous logarithmic transformation. Note that when $\lambda = 1$ this means that we do not make any transformation and that we keep the original variable except for a translation. For a sample of n observations (y_1, y_2, \dots, y_n) the procedure is to apply the same transformation to all values :

$$\{y_i \in R_+^*\} : y_i^* = f(y_i, \lambda) = \begin{cases} \frac{y_i^\lambda - 1}{\lambda}, & \text{if } \lambda \neq 0 \\ \log(y_i), & \text{if } \lambda = 0 \end{cases} \quad (3.10)$$

TABLE 3.8 – Skewness and kurtosis tests for normality before box-cox transformation

variable	Obs	Pr(skewness)	Pr(kurtosis)	Joint test Adj chi2(2)	Prob>chi2
Resid1	380	0.0000	0.0000	32.24	0.0000
Resid2	380	0.0000	0.0000	30.04	0.0000

TABLE 3.9 – Skewness and kurtosis tests for normality after box-cox transformation

variable	Obs	Pr(skewness)	Pr(kurtosis)	Joint test Adj chi2(2)	Prob>chi2
Resid1'	380	0.1918	0.0524	5.48	0.0646
Resid2'	380	0.4713	0.0590	4.10	0.1290

The results of Skewness and Kurtosis tests after Box-Cox transformation are presented in (table 9). The results of a joint test, demonstrate that we cannot reject the hypothesis that residuals are normally distributed, at least at the 0,06% and 0,12% levels of residual 1 and residual 2 respectively.

After all, we compare the results with transformed data (table 5) and those with non-transformed data (Table 10). The difference between the two estimation results is not significant, the signs of the coefficients, as well as the level of significance, are the same in both tables. Therefore, we can conclude that the non-normality of the residuals in our panel PMG model does not represent a problem in the estimation since it does not significantly modify the estimation results.

TABLE 3.10 – Linear ARDL estimations after transformation of variables (CEPC, EI, GDPPC, PDPC)

VARIABLES	ESTIMATION 1	VARIABLES	ESTIMATION 2
ECT	-0.3756592*** (0.0809748)	ECT	-0.4228918*** (0.0794227)
Short run relationship			
D.lnEI	0.1280985*** (0.0326845)	D.lnEI	0.1265906*** (0.0339629)
D.lnSMCPC	-0.0022783 (0.0074737)	D.lnSTPC	-0.0096316* (0.0052701)
D.lnGDPPC	0.0496938*** (0.0120546)	D.lnGDPPC	0.0530823*** (0.011645)
D.lnPDPC	-3.39423 (4.736236)	D.lnPDPC	-1.08599 (4.935834)
Long run relationship			
lnEI	0.1951194*** (0.0270875)	lnEI	0.1783426*** (0.0246677)
lnSMCPC	0.0270129*** (0.0076211)	lnSTPC	0.0141153** (0.005865)
lnGDPPC	0.106044*** (0.0053093)	lnGDPPC	0.0994283*** (0.0048403)
lnPDPC	-1.4680016*** (0.2450394)	lnPDPC	-1.226975*** (0.208191)
Constant	-1.14975*** (0.2732972)	Constant	-1.2251911*** (0.2570484)
Observations	361	Observations	361

Notes : Number in parenthesis indicate standard errors. “***”, “**” and “*” indicate respectively significant value at 1%, 5% and 10%.

3.5 Conclusion and policy implications

The relationship between stock market development, economic growth and energy use is well documented in the literature. However, there are only few studies that investigate the links between stock market development and environmental quality. Previous studies have demonstrated that the impact of stock market development on environmental quality is positive in developed economies and negative impact in emerging market economies (see e.g. Paramati et al, 2017). Moreover, the empirical study of Zafar et al., (2020) suggest a positive relationship between industrialization and carbon emission. Nevertheless, It is not yet clear from previous studies whether positive and negative shocks on stock market development increase or decrease environmental degradation. In trying to bridge this knowledge gap in the literature, this study investigates both the symmetric and asymmetric impacts of stock market development, energy efficiency on environmental quality across a panel of 19 emerging market economies over the period from 1995 to 2014.

Results from the symmetric effects of stock market development on carbon emissions demonstrates that stock market development indicators hurt the environment in emerging market economies. This result is in consonance with the study of Paramati et al. (2017). However, the nonlinear estimation results suggest that both positive and negative shocks on stock market development have negative effects on environmental quality. The linear long-run elasticities show that stock market development in emerging economies increase carbon emissions because development stock market has the potential to attract funds to finance production and manufacturing activities that lead to increase in energy consumption, especially fossil fuel energy in countries with weak environmental regulations. Consequently, this leads to an increase in the level of carbon emissions. Considering results from the asymmetric model, the long-run elasticities reveal a new impact of stock market development indicators on environmental quality. The empirical findings show that negative shocks in stock market capitalization have a greater impact than positive shocks on carbon emissions in emerging market economies.

Given the above findings, our study provides some important policy implications for policy makers and investors in the emerging market economies. First, the implications of our findings suggests that although developed stock markets may provide sources of funds for the emerging markets, this may have a negative impact on environmental quality when environmental regulations on reducing emission is not strictly enforced in emerging countries. Secondly, positive shocks in stock market capitalization hurt the environment because when stock market is developed there are more sources to finance production and manufacturing which increase emissions by increasing pollutant energy consumption. However, negative shocks in stock market capitalization may also increase emissions. This may be expressed in negative changes in stock market capitalization that means less sources of funds to finance new technologies and renewable energy project which tend to promote the use of fossil fuel energy ; there by in-

creasing carbon emissions.

Taken together, these results suggest that the development of stock market as measured by stock market capitalization per capita in emerging market economies has a substantial negative impact on environmental quality. These demonstrate that stock market activities hurt the environment by increasing carbon emissions in emerging market countries. This implies that stock market policies that seek to enforce compliance to environmental regulations may not have been effective in emerging markets. Therefore, this study recommends that policy makers in these emerging economies should establish more environmentally friendly policies that will promote the transition to green technologies and renewable energy sources. Finally, policymakers in emerging market economies need to take into account the effect of negative shocks of stock market on carbon emissions when they consider limiting manufacturing activities to achieve the environmental objective. Some measures must be introduced, such as supporting companies in the decarbonization of their production, combating waste, developing innovative projects and developing the carbon emission trading market, in order to ensure developed financial markets with minimal environmental impact.

Chapitre 4

Asymmetric connectedness among stocks, energy, and carbon emissions trading systems in Europe and China

Abstract ¹

With the rapid expansion of the global carbon trading market, the correlation between carbon prices, energy prices, and the stock market has attracted increasing attention. This paper examines the asymmetric connectedness among stock markets, energy prices, and emission permit prices. Specifically, we focus on the European Emission Trading system and China's primary carbon permit market. For this purpose, we use a multivariate asymmetric GARCH-BEKK methodology to capture the complex dynamic conditional correlations among stocks, carbons, and energy markets. This approach enables us to analyze the temporal linkages among these markets in different market situations, providing a deeper understanding of spillover effects between them. Our results highlight a contrast between short-term spillover effects in China and long-term effects in Europe, suggesting the need for different policy approaches to manage market volatility and promote sustainability. These findings have important implications for policymakers in encouraging the transition to a low-carbon economy and for investors, who should know the potential risks and opportunities in these markets.

1. This chapter is an article written with co-authors : Christian UROM, and Talel BOUFATEH

4.1 Introduction

With the huge emissions of greenhouse gases, global warming has become a significant challenge to the sustainable progress of humanity. Over 100 nations worldwide ratified the "Kyoto Protocol" in 1997, aiming to address the challenge of climate change. Recently, the COP26 conference negotiated for 197 nations to achieve more ambitious targets for reducing greenhouse gas emissions by 2030. In fact, more and more countries and regions have established a carbon market to meet this challenge. Such as the European Union Emissions Trading Scheme (EU ETS), the United Kingdom Emissions Trading Scheme (UK ETS), and the recent Chinese carbon market. As a result, carbon allowances represent a novel class of financial tools aimed at mitigating the scope and consequences of global warming and climate change. This implies that the significance of the carbon market will keep growing in the upcoming years.

The European Union (EU) is at the leading edge of efforts to mitigate the effects of climate change and reduce carbon emissions. One of the primary methods employed by the EU to achieve this is by putting into effect the Emissions Trading Scheme (ETS), which stands as the largest carbon market globally. The ETS caps the amount of carbon that participating companies can emit and allows them to trade carbon allowances, providing an economic incentive to reduce their emissions.

In contrast, China has been slower to adopt comprehensive carbon reduction measures, although both have made progress in recent years. China has implemented a pilot emissions trading scheme in some regions, but it is not yet as comprehensive as the EU's emissions trading scheme. The pricing of carbon allowances significantly influences the operation of the ETS. This aspect is linked to achieving the carbon emissions reduction target and interests various stakeholders, including governors, companies, and investors. Companies decide to buy or sell carbon allowances based on carbon price levels, while investors base their actions on variations in carbon prices.

The significant price volatility of carbon emission allowances has greater consequences than that of several financial assets or commodities to a given degree (Fan and Todorova, 2017). This is due to the nature of carbon emissions and their environmental impact. Carbon emissions contribute to climate change, which can have long-term and far-reaching consequences for ecosystems, the global economy, and human health. Therefore, the price of carbon allowances is closely linked to efforts to mitigate the effects of climate change. Volatile carbon prices can affect the economic sustainability of projects to reduce emissions and can also impact the financial performance of companies that emit large amounts of carbon. The pricing of carbon allowances is, therefore, a particularly sensitive issue that can have significant consequences for the environment, the economy, and society as a whole.

From an economic and financial perspective, The sharp fluctuations in the price of emission allowances not only impact the decisions of companies and the profits and losses of financial operators but also influence the expectations of all participants involved. Historical data on carbon prices reveal significant fluctuations in European Union Allowances (EUA) and Chinese Carbon Emission Allowances (CEA) since their establishment. The existence of such a threat has serious implications for mitigating risk through hedging, arbitrage, promoting economic development, and ultimately achieving national carbon reduction goals. Comparing the effectiveness of carbon markets in Europe and China, considering spillover effects on energy and stock markets would be an interesting undertaking to understand better the impact of different policy approaches on emissions reductions and economic performance.

The European Emissions Trading Scheme (ETS) has been operating for over a decade and has been a significant success in reducing carbon emissions. However, there has been some debate regarding how the ETS affects energy and stock markets. Some studies suggest that the EU ETS may have a favorable effect on investment in sustainable energy and creativity in eco-friendly technologies, or it may also result in elevated energy prices and reduced competitiveness for specific industries (Huang et al (1996)). In China, the pilot emissions trading scheme has only been operational since 2013 and has not yet been fully implemented nationwide. Nevertheless, there have been encouraging indicators, including incorporating carbon markets in China's 14th Five-Year Plan and the aspiration to attain carbon neutrality by 2060. The effect of the carbon market on energy and stock markets in China is still uncertain. Still, given the size of China's economy, any such policy changes will likely have significant global implications. Therefore, comparing the efficiency of carbon markets in Europe and China while considering the spillover effects on energy and stock markets could provide valuable insights into developing effective policies to reduce carbon emissions and promote sustainable economic growth.

At the same time, the carbon market, characterized by its political influence, stands out among energy commodity markets (Remes et al., 2014). Given the multitude of factors propelling fluctuations in this market, its influence on interconnected markets, the growing trend of globalization, and the process of financialization of carbon (Berta et al., 2017), it is crucial to carry out a comprehensive analysis of the transmissions of information and shocks between the carbon market and other markets, in particular the financial and energy markets. Such an analysis is paramount to environmental policy analysts to facilitate the development of accurate policies. At the same time, the research on the correlation between the stock market and the carbon emissions market has recently gained popularity. However, most of these studies have concentrated on employing a linear approach. Nevertheless, it should be noted that the non-linear behavior of variables is widely used in the social sciences, economics, and finance. The reason is the volatility of market variables over time, which interact with each other nonlinearly (Mareno and Silva, 2016 ; Mishra et al., 2023 ; Badeeb et al., 2018).

In general, Non-linear effects can result from economic and financial crises, changes in the economic cycle over time, or the complex nature of financial markets. In addition, the stock market is continually influenced by financial crises, policy changes, and many other factors. The linkages between stock, carbon, and energy markets should be explored in China for several reasons. First and foremost, China holds the distinction of being the largest contributor to greenhouse gas emissions, significantly impacting global carbon emissions. In addition, China has invested heavily in new energy and is a major driver of global economic development. However, there are currently no studies comparing the relationship between these three markets in China and Europe, highlighting the need for this research.

In addition, Carbon price fluctuations have been widely studied by academics worldwide, particularly in Europe and China. Recently, an increasing amount of research has centered on the spillover effect from carbon markets to various energy markets (see Kim et al., 2020; Naeem et al., 2020). However, the interconnection and spillover effects among carbon, equity, and energy markets have not received extensive research attention. In this context, understanding extreme movements in energy prices, particularly oil and green bonds, is critical to understanding movements in carbon prices. An accurate measure of the extreme risks associated with these markets is essential to effectively hedge risks and manage investments in both the European and Chinese carbon markets. This paper aims to examine the degree of connection between these markets and shed light on the dynamics of their interactions and their potential impact on carbon prices. Asymmetric multivariate GARCH methods can help to investigate this research objective. Therefore, we use the asymmetric multivariate Garch model BEKK in this study to compare the connectivity between different markets in Europe and China.

4.2 Literature review

With growing concerns about the functioning of the carbon market, researchers recognized the urgent need to study the possible links between the carbon market and other financial markets. In response, a growing collection of empirical studies has emerged to elucidate this issue.

Emission allowances' valuation is determined by the interaction between availability and market demand, influenced by many factors, including weather conditions, industrial production, manufacturing scale, and macroeconomic and financial indices. A high carbon price encourages participants to adopt energy-saving technologies and limit carbon emissions. However, this increases companies' operating costs and can hinder their development, ultimately impacting on economic growth. On the other hand, a relatively stable carbon price favors the transition from a carbon-intensive economy to a sustainable economy based on market factors. By contrast, exceptionally low carbon prices hinder progress towards reducing carbon emissions and promoting energy savings.

Recently, emission allowance has been defined by a financial characteristic. Particularly, The purchase of emission allowances (EAs) is not limited to carbon-emitting companies alone ; it is also undertaken by investors and speculators seeking to mitigate risks or capitalize on potential profits. Moreover, climate policy uncertainty is taken into account in the options market, and EA price formation closely resembles that of other standard commodities (Fan and Todorova, 2017). Compared to other financial assets and commodities, EA is relatively young. The EU Emissions Trading Scheme (EU ETS) is the pioneer of global carbon markets. The price behavior of EU allowance has attracted great attention from researchers recently.

The European carbon spot prices have a random behavior characterized by non-stationarity and jump (Conrad et al., 2012). Using a fractionally integrated asymmetric power GARCH model (Chevalier, 2011) demonstrates that EUA are dynamics. Moreover, the findings indicate that high-frequency EUA returns exhibit persistent memory, a power effect, and asymmetry within their secondary conditional moments. (Wen et al., 2022) examined the effects of investment timescales and speculators' expectations of returns on carbon price behavior. The findings imply that as the investment timescale increases, the likelihood of bearish trends rises while speculators' return expectations decrease, resulting in reduced distortions in carbon price behavior.

Lately, research has focused mainly on assessing the ability of the energy market to effectively anticipate carbon market behavior, exploring potential risks and information between the carbon market and various other markets, particularly financial markets, and studying the wider macroeconomic consequences arising from their interconnection. This is especially important as the interaction between the carbon market and the various financial markets is growing, driven by increasing capitalization and trading activity, in parallel with the growing integration of global financial markets.

Looking at the literature that examines the carbon-energy-finance relationship, we can distinguish two main research lines. The first line has examined the volatility linkage between the carbon market and energy markets. For example, Chen et al. (2022) found a changing correlation between energy and carbon emission factors through an MGARCH model. Ji et al. (2019), meanwhile, assessed the effectiveness of smooth-transition conditional correlation GARCH models in capturing the carbon-energy relationship during the second phase of the EU ETS. This study finds that correlation depends on market uncertainty.

Especially, The expectation of high stock market volatility significantly amplifies the correlation between carbon and equities. Using comparable models, Sun et al., (2020) show significant volatility spillovers and correlations between carbon prices and the values of coal, natural gas, and crude oil. In a recent work, Liu et al (2023) categorized

existing research into the relationships between energy, carbon, and financial markets into three categories. The first category of studies refrains from dissecting stock prices and oil prices in their empirical investigations, choosing instead to focus on diffusion effects between energy and alternative futures contracts (see, for example, Barbaglia, 2020 ; Gong et al., 2021 ; Guo et al., 2021).

Research of the second type focuses on the spillover phenomenon between energy and stock prices without differentiating between demand and supply shocks. In subsequent analyses, the results often reveal the scarcity or weakness of the link between energy and financial markets (for example, explore Chang et al., 2018 ; Gonzalez and Espinosa, 2019). The third category of studies, based on the foundations laid by Liu et al. (2023), goes further in segmenting oil prices into demand and supply shocks, building on the foundations laid by Hu et al. (2020). In addition, Liu et al. (2023) studied the time-varying connectivity between electricity, carbon and oil demand and supply shocks, and clean energy markets using the spillover methodology proposed by Daskalakis and Markellos (2009). They observed an increase in connectivity both during periods of global financial crisis and in the era of the shale oil revolution. In addition, they demonstrated that global connectivity tends to be more pronounced in the short term than in the long term. Consequently, fluctuations in energy prices, which reflect a dimension of uncertainty, undoubtedly play a role in the evolution of carbon prices.

4.2.1 Carbon market-energy market nexus

The topic of the carbon market has produced much discussion in recent research studies. Many of these studies have demonstrated a strong interconnection between carbon markets and energy markets, particularly those involving fossil fuel energies (Aatola et al., 2013 ; Zhang et al., 2015 ; Chevallier, 2011b ; Moreno and Da Silva, 2016 ; Ji et al., 2019). Two main reasons explain this relationship. First, Fossil fuels still represent 84% of global energy consumption (Statistical Review of World Energy, 2020). As a result, energy consumption is the key factor of carbon emissions and global warming. In addition, fossil fuel energy presents the primary fuel for power generation companies, which leads to volatility in fossil fuel energy. Carbon prices become a major factor for power generation enterprises. Balcilar et al. (2016) found significant volatility and time-varying risk transmission from energy markets to carbon markets in the European market via the MS-DCC-GARCH model.

In addition, numerous studies have been carried out to investigate the link between carbon emissions trading market and energy markets. Early research indicated that energy prices had a significant impact on carbon prices. This finding was confirmed by several studies conducted by (Zeng et al., 2017), (Zhao et al., 2018 ; Jiang et al., 2018). Nevertheless, similar studies have also revealed variations in the impact of various energy price categories on carbon prices. For example, (Guo 2015) found that in China, domestic crude oil prices had a more significant

impact on carbon prices than other energy prices. (Jiang et al, 2018) investigated this relationship from a dynamic perspective, oil prices had a negative impact on carbon prices up to three weeks earlier (Zhao et al. 2018), found oil prices provided a more accurate trend. Subsequent studies have examined the relationship between CET and energy market prices at different stages. As an example, the work of Marimoutou and Soury (2015) focused on Phases II and III of the EU ETS, finding that the most significant impact on carbon prices occurred in the period from mid-2011 to early 2012, with Brent oil prices playing a central role. In terms of market risk, Tan and Wang (2017) found that during Phase II, increased oil price volatility exacerbated risk within the European ETS.

Many researchers have investigated the spillover effects between carbon trading markets and their interconnected counterparts. One group of researchers focused on examining volatility spillover effects within pilot carbon trading programs in China, using conventional copula and VAR models. The results suggest volatility spillover effects among these Chinese carbon trading pilot programs. At the same time, price variations for each pilot were modest and largely influenced by project-specific factors (see Zhu et al., 2020 ; Guo, 2021).

Another group of researchers studied the volatility spillover effects between the carbon and energy markets in the European Union (EU) region. To do so, they primarily used the TVP-VAR-SV, DCC-GARCH, and BEKK-GARCH models (Zhang and Sun, 2016 ; Gong, 2021). Their findings revealed a significant spillover effect between the carbon trading market and the fossil fuel market, with the coal market having the greatest impact on the carbon trading market. In addition, they found that the price of Brent crude oil also played a crucial role in driving the EU carbon market price.

As China's economy continues to expand and adopt mitigation policies to reduce greenhouse gas emissions, research on its Carbon Emission Trading (CET) markets is also increasing (Jiang et al., 2014 ; Wen et al., 2020a ; Wen et al., 2020b ; Zhang and Sun, 2016 ; Zhang and Zhang, 2016 ; Zhao et al., 2020 ; Zhu et al., 2020). Although China is the largest and fastest-growing country and the world's largest carbon emitter (Liu, 2016 ; Zheng et al., 2019), research on the Chinese carbon emissions market does not adequately capture its importance within the CET market.

Numerous investigations have examined the correlation between the CET market and energy markets, particularly in the crude oil market. A good example is the study by Jalil and Feridun (2011), which examined the influence of growth, energy, and financial development on the environment in China. Their findings revealed that carbon emissions were primarily influenced by income and energy consumption, potentially reinforcing the interrelation between energy and CET markets.

In addition, there are two ways in which the green bond market and carbon market interact. Firstly, if power com-

panies' carbon emissions are limited, green bonds issued by these companies to fund climate change mitigation projects can lead to carbon emissions leakage. This is because the mitigation achieved through the projects can lower the scarcity of EUAs under the cap, allowing emissions to shift instead of decreasing overall (Heine et al., 2019). Secondly, the volatility of prices explains the relationship between green bonds and EUA markets. A stable EUA price results in a more reliable return on investment for green projects, which increases demand for green bonds (Heine et al., 2019).

4.2.2 Stock market-carbon market nexus

Most research into the interaction between the carbon market and the stock market focuses on a global view of the stock market. Numerous investigations by (Koch et al., 2014) and (Ji et al., 2021) have demonstrated a notable influence of the EU stock market on the European carbon market. (Oestreich and Tsiakas, 2015) delved deeper into the link between the German stock market and the European carbon market, revealing that companies obtaining free carbon permits outperformed those without. Subsequent studies, such as that by Luo and Wu (2016), examined the evolving relationship between the European carbon market and stock markets in the US, China and the EU. These studies revealed that the US and EU stock markets showed stronger correlations with the EU CET market than the Chinese stock market. In addition, (Jimenez-Rodriguez, 2019) substantiated the link between the EU CET market and stock markets by developing a model with time-varying parameters.

Understanding of the implemented carbon market in China and its link with the stock market remains limited. However, a few studies have been conducted in this area. Zeng et al (2017) examined the carbon emission allowance price in Beijing and investigated its dynamic relationship with economic development and energy prices. They found a positive correlation between the price of carbon emission allowances, the price of crude oil, the price of natural gas, and economic development in Beijing. Using a vector autoregression (VAR) model, Jiang et al. (2018) investigated the impact of coal prices, oil prices, and stock market indices on carbon prices in China. They observed that coal prices and stock market indices had negative effects on carbon prices, while oil prices initially had a negative impact on carbon prices for the first three weeks and then showed positive effects.

Moreover, Fan and Todorova (2017) conducted empirical research into the links between carbon prices and macroeconomic risk in China's pilot cap-and-trade system. They found that indices in the energy, industry materials, and utilities sectors were positively correlated with carbon allowance prices on the Shenzhen and Guangdong carbon trading markets.

Nowadays, many studies focus on exploring the asymmetrical link between carbon trading market and stock market. Furthermore, these non-linear effects can be determined by comparing the impacts of negative and positive

return systems. Wen et al. (2020) examined the asymmetric relationship between carbon emission trading market and stock market in China using NARDL model. The results reveal a significant negative asymmetric link between the carbon market and the global stock market. In addition, the impact of rising carbon prices on stock prices is significantly more significant than their fall.

Numerous studies have demonstrated the interconnection between the carbon market and the stock market (Ji et al., 2019; Tan et al., 2020; Yuan and Yang, 2020; Li et al., 2021). In addition, the researchers studied the asymmetric interconnection between these two markets in the Chinese context. While there is no significant influence of the stock market on carbon prices, Li et al. (2020) identified a modest spillover effect between the Chinese carbon market and the electricity sector. This apparent divergence highlights the need for further investigation to uncover hidden information. In addition, Venmans (2015) identified a favorable correlation between EUA prices and the share prices of regulated companies.

In addition, researchers have analyzed the correlation between carbon prices and stock markets in different countries. For example, applying the orthogonal GARCH model, Luo and Wu (2016) noted that the links between EUA carbon prices and stock markets are stronger in the US and Europe than in China.

The review of the literature reveals several issues that are worth examining. First, carbon trading markets in European countries have been the subject of a great deal of research because of their historical nature and maturity. Few studies have been conducted on the link between the stock market and the Chinese carbon market, which has a much shorter history. Secondly, most of these studies have used linear approaches to establish relationships, and only a few have recently used non-linear methods with mixed results. However, the asymmetric relationship between stock and carbon markets in China has not been widely explored. This study will address this issue by examining the asymmetric and nonlinear views in the long and short run using the asymmetric Multivariate GARCH BEKK method.

4.3 Data and methodology

4.3.1 Data

In this investigation, we use a well-balanced daily data set from 2018 to 2021. Before starting the estimation process, all variables were transformed into their respective log-difference equivalents. Table 1 presents the definitions of all variables used in this study, as well as their sources. Table 2 gives an overview of the descriptive statistics for all variables for China and Europe.

Standard deviations show that the overall unconditional volatilities of Chinese market indices exceed those of European markets. SZA, HBEA, and SHSTOCK show positive skewness values, indicating a right-angled distribution. At the same time, all markets show kurtosis values above 3, signifying pronounced peaks and heavier tails. The results of the Jarque-Bera test confirm that the data adhere to a non-normal distribution.

Furthermore, the Dickey-Fuller (ADF) test, developed by Dickey and Fuller in 1981, is a widely used unit root test that helps to determine the order of integration of variables. The ADF test examines the null hypothesis that the series has a unit root, indicating non-stationarity, against the alternative hypothesis of stationarity.

TABLE 4.1 – Data description

Variables	Définitions	Temporel intervals	Sources
SHSTOCK	Shenzhen stock market index : Component Index Price History	From June 2019 to March 2021	Bloomberg database
STOXX	STOXX Europe 600 EUR Price Index Price History	From January 2019 to October 2021	Bloomberg database
GDEA	Hubei carbon emission permit trading market : Component Index Price History	From June 2019 to March 2021	China Carbon Emissions Trading Network
EXX	EUA carbon futures index Price History	From January 2019 to October 2021	Bloomberg database
SSEGB	Chinese Green bond Price History	From June 2019 to March 2021	Bloomberg database
EUGB	European Green bond Price History	From January 2019 to October 2021	Bloomberg database
WTI	Brent crude oil Price History	From January 2019 to October 2021	Bloomberg database

Applying the ADF test to all indices in European and Chinese markets, our results demonstrate that at a 1% statistical significance level, all series become stationary at the first difference. This indicates that the prices in these markets exhibit persistence that can be removed through first differencing and suggests that past prices have limited predictive power for future prices.

Fig.1 and Fig.2 present, respectively, the volatility in Chinese markets and European markets, respectively. In Figures 1 and 2, we can observe the clustering characteristics of volatility and time-varying.

More significant return fluctuations are observed in the European than in the Chinese stock market. It is also observed that the COVID-19 pandemic generated a huge shock in several markets. In Europe, the shocks on the stock market, the energy markets, and the green bond market occurred at the beginning of 2020, while in China, it is observed that the shocks related to the COVID-19 crisis affected the Chinese equity, green bond, and carbon markets at different times. The Guangdong ETS has the highest volatility, while the Shenzhen ETS has the lowest volatility in return fluctuations compared to the Hubei ETS., perhaps because Guangdong is one of the largest provinces in China with a highly developed economy and a high level of industrial activity, which could make it more vulnerable

to carbon price fluctuations.

TABLE 4.2 – Descriptive statistics

Variables	Europe				China			
	EXX	STOXX	WTI	EUGB	GDEA	SHSTOCK	WTI	SSEGB
Obs	729	729	729	729	636	636	636	636
Mean	0.0009	0.0003	0.0004	0.0001	0.0023	0.0004	-0.0006	-0.0002
Max	0.1281	0.0807	0.2166	0.0484	0.0621	1.7976	0.2166	0.0055
Min	-0.1803	-0.1219	-0.3033	-0.0544	-0.0634	-1.7678	-0.3033	-0.0032
Std. Dev.	0.0278	0.0101	0.0269	0.0039	0.0163	0.1014	0.0350	0.0005
Skew.	-0.3907	-1.9047	-2.1310	-1.2502	0.1218	0.4214	-1.7854	1.3196
kurt.	6.6054	24.3686	30.9725	82.8807	5.8024	301.9715	23.9983	28.4216
JB test	1645***	4.0e+04***	4.0e+04***	5.2e+05***	1634 ***	5.3e+06***	1.9e+04***	2.4e+07***
ADF	(-27.318)***	(-27.620)***	(-29.047)***	(-31.001)***	(-24.979)***	(42.318)***	(-23.070)***	(-18.801)***

Note : 'Obs', 'Max', 'Min', 'Std.Dev.', 'Skew', 'Kurt.' denote respectively Observations, Maximum, Minimum, Standard Deviation, Skewness, Kurtosis. 'JB test' denotes Jarque-Bera test. 'ADF' denotes the Augmented Dikey-Fuller test. *** denotes the rejection of the null hypothesis at the significance level of 1%

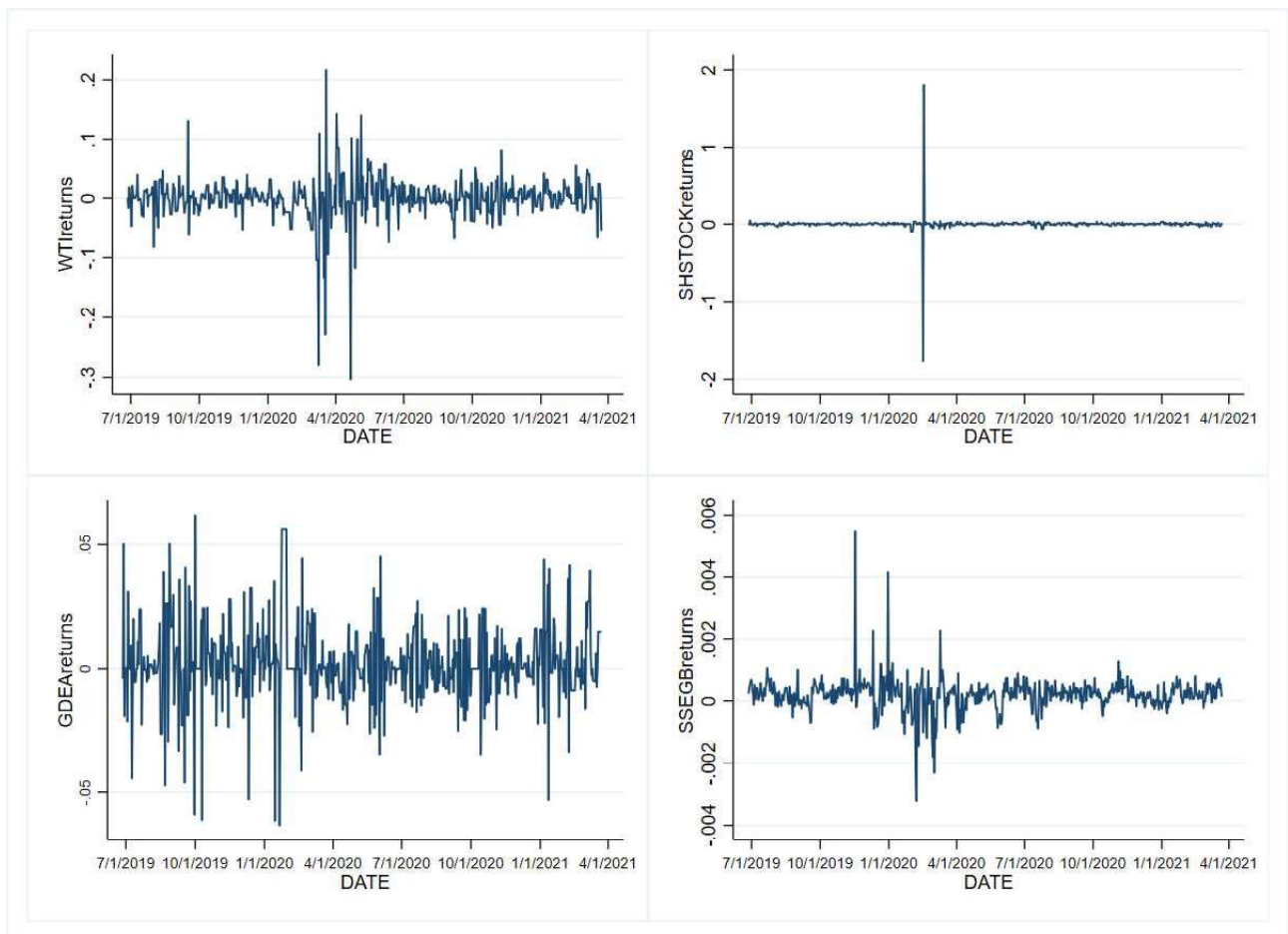


FIGURE 4.1 – Plot of Chinese markets returns

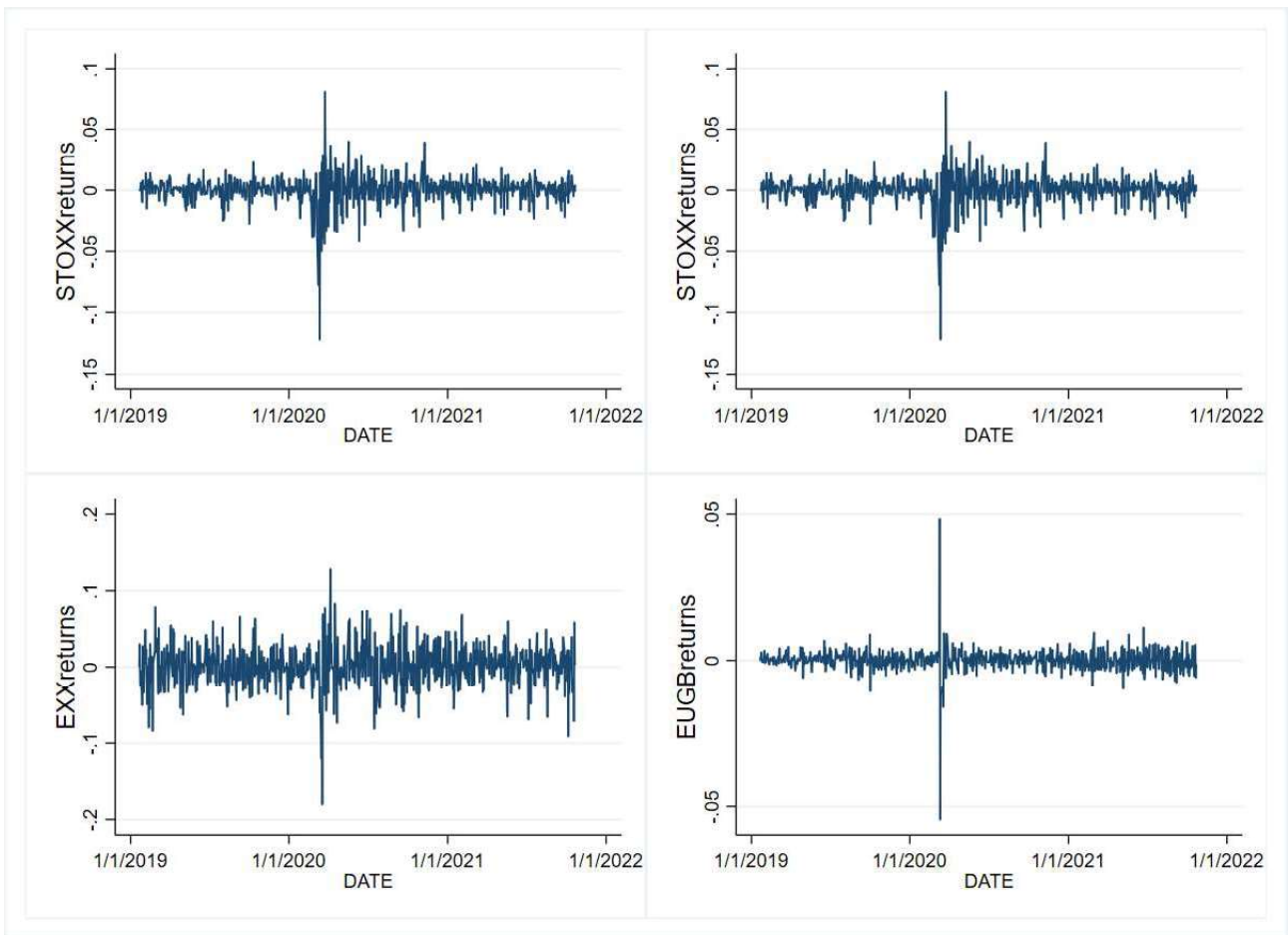


FIGURE 4.2 – Plot of European markets returns

4.3.2 Methodology

Our study aims to explore the interaction between the stock market, the energy market, and the carbon market in Europe and China. In addition, we aim to examine the risk transfer characteristics and dynamic correlations between these interconnected markets. Multivariate GARCH models (MGARCH) are commonly used to study the co-movements between financial market uncertainties. In this regard, the BEKK and DCC models have been widely used to investigate the spillover effects of Intermarket volatility and to capture correlation clusters in financial time series, commodities, and economic indicators.

To address the complex interactions and dependencies between these markets over time, we believe that the VAR-BEKK-GARCH and VAR-DCC-GARCH models are the most appropriate methodologies for achieving our research objectives and answering our research question. Using these models, we can gain a deeper understanding of the risk transfer mechanisms between different markets, which can inform investors, policymakers, and other stakeholders about potential risks and opportunities associated with these markets.

Our study focuses on the asymmetric volatility spillover and dynamic conditional correlation between stock markets, energy, and carbon markets in Europe and China, using the asymmetric VAR-BEKK-GARCH model and VAR-DCC-GARCH model. It is important to note that the endogenous effect can be significantly reduced by increasing the number of variables when studying the spillover effect between several markets, as suggested by Bauwens and Rombouts in 2006.

Asymmetric VAR-BEKK GARCH model

The measure of return and volatility spillovers is based on vector autoregression (VAR) models, a univariate VAR can be presented by :

$$R_{i,t} = C_1 + \beta_1 R_{t-1} + \beta_2 R_{t-2} + \dots + \beta_k R_{t-k} + \varepsilon_t \quad (4.1)$$

$$\varepsilon_t \sim N(0, H_t) \quad (4.2)$$

Here, R denotes a returns vector at time t , C signifies the constant vector, the matrix β represents the estimated coefficients, ε stands for the residual vector, and k denotes the lag order.

Firstly, the VAR model, an extension of the univariate autoregressive (AR) model, incorporates the central variables of the economic scenario as endogenous variables. It employs the lagged values of all these endogenous variables

in its formulation.

Secondly, the GARCH BEKK (p, q) model (Engle and Kroner, 1995) is gaining popularity due to a specific advantage : it provides a positive variance-covariance matrix without imposing restrictions on the parameters. This feature reduces the number of estimated parameters and simplifies the estimation process. Therefore, to increase the number of estimated parameters, the model order is generally set to 1.

$$H_t = H_t = CC' + Ae'_{t-1}e_{t-1}A' + Bh_{t-1}B' \quad (4.3)$$

and,

$$h_{it} = C_i + \alpha_i e_{i,t-1}^2 + \beta_i h_{i,t-1} \quad (4.4)$$

$$e_{it} = v_{i,t} + h_{i,t}, \quad v_{i,t} \sim N(0, 1) \quad (4.5)$$

Eq.(5) gives the relationship between the conditional variance $h_{i,t}$ and the residual term e_{it} . Thus, the asymmetric version of the BEKK-GARCH model is given by :

$$H_t = C_1C_1' + A(e'_{t-1}e_{t-1})A' + Bh_{t-1}B' + D_1(z'_{t-1}z_{t-1})D_1' \quad (4.6)$$

The components H(1,1), H(2,2), H(3,3), and H(4,4) of the matrix H represent the conditional variances of the stock market, the carbon market, the oil market, and the energy markets respectively, In this context, h_{ij} denotes the conditional covariance between variables i and j . The matrix A embodies the ARCH elements, where its constituents encapsulate the ARCH influence stemming from fluctuations across the four markets. These coefficients encapsulate the repercussions of external shocks on market dynamics, while the off-diagonal elements elucidate the inter-market transmission effects. On the other hand, the B matrix represents the GARCH coefficients of the model. The elements B(1,1), B(2,2), B(3,3), and B(4,4) denote the GARCH effect associated with each of the respective markets. indicating the persistence of volatilities within each market individually. The non-diagonal elements of matrix B illustrate the volatility spread between the different markets. As the volatility spillover effect continues, the aggregate of ARCH and GARCH coefficients approaches unity.

Matrix D shares a similar form with matrices A and B, denoted by a column vector of k dimensions z_{t-1} . If $e_{t-1} \leq 0$, z_{t-1} represents a negative shock or bad news, otherwise z_{t-1} is equal to zero. Therefore, matrix D evaluates the asymmetric impacts between the four markets.

DCC GARCH model

To accurately study the time-varying spread of volatility across markets, we employ the DCC-GARCH model developed by Engle (2002), which has been widely used in recent research. Yan et al. (2019) used the DCC-GARCH model to investigate volatility contagion effects in the correlation between oil and equities. Simultaneously, Chen et al. (2019) explored the link between crude oil and new energies, and Gonzalez and Espinoza (2019) looked at the phenomenon of contagion within exchange rate markets. More recently, Aswini et al. (2022) applied the DCC-GARCH model to examine connectedness between commodity markets.

In this study, we use the percent continuously compounded returns as $r_t = 100\ln(p_t/p_{t-1})$, where p_t denotes the carbon prices, stock market indices, and energy price at period t . The DCC model of Engle is defined as :

$$\begin{cases} H_t = D_t R_t D_t \\ D_t = \text{diag}(h_{11t}^{1/2} \dots h_{mnt}^{1/2}) \\ R_t = \left(\text{diag}(Q_t^{-1/2}) \right) Q_t \left(\text{diag}(Q_t^{-1/2}) \right) \end{cases}$$

where R_t is the time-varying correlation matrix and $Q_t = (q_{ijt})$ are the nn symmetric positive definite matrices defined as :

$$Q_t = (1-ab)\bar{Q} + au_t u_{t-1} + bQ_{t-1} \quad (4.7)$$

$u_{t-1}u_{t-1}$ represent the lagged function of the standardized residuals. \bar{Q} is the nn unconditional covariance matrix of u_t , and Q_t is the unconditional variance between series x , and y . The conditional covariances are defined as follows :

$$h_{xy,t} = \frac{q_{xy,t} \sqrt{h_{xx,t} h_{yy,t}}}{\sqrt{q_{xx,t} q_{yy,t}}} \quad (4.8)$$

where,

$$h_{xx,t} = \omega_x + \alpha_x \epsilon_{t-1}^2 + \beta_x h_{xx,t-1}, \quad \text{for } x = 1, \dots, n. \quad (4.9)$$

4.4 Empirical results

Asymmetric VAR-BEKK-GARCH results

Before performing the VAR-BEKK GARCH estimation, it is essential to determine the most appropriate shift order for the VAR model. Once the best lag order has been determined, the model can be subsequently estimated.

Table 3 displays the outcomes of the lag order selection process based on two criteria : the Final Prediction Error

criterion (FPE) and the Akaike Information Criterion criterion (AIC). The analysis demonstrates that for China, the determined optimal lag order is 3, while for Europe, the optimal lag order is found to be 4. These findings suggest that the variables in the Chinese model exhibit integration at the order of 3 (I(3)), whereas the variables in the European model exhibit integration at the order of 4 (I(4)). Consequently, VAR models are estimated using the identified optimal lag order for each respective series.

TABLE 4.3 – Lag selection for the VAR model

Lag order	China		Europe	
	FPE	AIC	FPE	AIC
0	9.2e-16	-23.2665	7.9e-16	-23.4203
1	6.6e-16	-23.5979	7.1e-16	-23.5292
2	5.9e-16	-23.7204	6.6e-16	-23.6089
3	5.6e-16*	-23.7675*	6.4e-16	-23.6286
4	5.6e-16	-23.7619	6.4e-16*	-23.632*

The next step is to estimate the three-dimensional asymmetric BEKK-GARCH (1,1) model using the BEFGS algorithm, which aims to optimize the model. The results of this estimation procedure are shown in Table 4. Matrix A includes elements indicating conditional ARCH effects, quantifying short-term persistence, while matrix B consists of elements representing conditional GARCH effects, measuring long-term persistence. Particular attention is paid to analyzing GARCH effects arising from heteroscedasticity, given its role as a fundamental source of volatility propagation across markets.

In the European model, our analysis reveals statistically significant conditional ARCH effects specific to each market ($A(i,i)$) at a significance level of 1%, indicating the influence of short-term shocks on individual markets. Similarly, the conditional GARCH effects for each market ($B(i,i)$) within matrix B also exhibit significance at the 1% level, implying the impact of market-specific volatility. It is worth noting that the estimated values of $A(i,i)$ are generally lower than their corresponding estimated values of $B(i,i)$, suggesting that most markets exhibit a long-term persistence (GARCH) of their own volatility greater than the short-term persistence (ARCH), except for the green bond market.

However, the results of China's models demonstrate significant differences. Only the ARCH term ($A(2,2)$) coefficient of the carbon market is significant at the 1% level in the short term. This indicates that the Chinese carbon market is influenced by its own shocks. On the other hand, the GARCH term reveals significant spillover effects of own volatility in the long run, particularly in energy markets and the carbon market.

These differences in the results can be attributed to various factors. Firstly, the European market might be more integrated and interconnected, leading to stronger interdependencies and spillover effects among its markets. Se-

condly, the policy responses and market structures in Europe and China could differ, resulting in varying market dynamics and volatility transmission patterns.

Therefore, the European model demonstrates significant short-term and long-term volatility effects in each market, with greater long-term persistence. In contrast, the Chinese model shows significant short-term volatility effects in the carbon market and significant long-term spillover effects in energy markets and the carbon market. These disparities highlight the unique characteristics and dynamics of each market, underscoring the importance of considering regional specifics when analyzing market behavior and volatility transmission.

In addition to the notable levels of conditional volatility within various markets, there are also considerable spillover effects of volatility across multiple markets. In the short run, for Europe, notable persistence is evident through short-run shocks between the stock market and the carbon market, highlighted by the significance level of 1% for $A(1,2)$ and the lack of significance for $A(2,1)$. On the other hand, in the long run, there are significant volatility transfers between the European stock market and the EU ETS, represented by the significance of $B(1,2)$ and $B(2,1)$ at the 10% and 1% levels, respectively.

Empirical results show a significant relationship between the carbon market and the European short-term green bond market. In addition, a significant link is observed between the carbon market and other long-term markets. More specifically, this study identifies spillover effects from the carbon market to the stock market. However, the spillover effect in the opposite direction seems relatively weak.

In addition, the analysis reveals that oil prices have a spillover effect on the European carbon market only in the short term. This finding can be attributed to the interconnectedness of the global energy system, where short-term shocks to oil prices have a transitory impact on the carbon market. These results are in line with research by Li et al (2022).

In addition, the results for China indicate that the carbon market has closer links with other markets in the short term than in the long term. In particular, Guangdong's carbon market shows the highest level of interaction with energy and stock markets in the short term. This can be attributed to the Guangdong economy's heavy reliance on energy-intensive industries and carbon-intensive sectors.

Interestingly, the results reveal a positive knock-on effect of the stock market on the carbon market in the long run. This result is in line with the research conducted by Wen et al. (2020). Therefore, changes in oil prices could indirectly impact China's carbon market through their knock-on effects on the stock market, which then affects the carbon market.

These results underline that the stock market acts as a transmission channel, propagating oil price shocks to the carbon market in China. They underline the importance of considering the role of the stock market as a shock transmission channel and the indirect impact of oil price fluctuations on the carbon market.

Matrix D, as displayed in Table 4, provides insights into the presence of asymmetric volatility spillover effects. Notably, in China, all four markets exhibit significant asymmetric coefficients. Specifically, the coefficient of the stock market ($D(1,1)$) is negative and significant at the 1% level, indicating that negative news tends to increase the stock market's volatility. On the other hand, the coefficients of the carbon and green bond markets are positive and significant, suggesting that negative news has the opposite effect by increasing the volatility of these markets.

In contrast, the results for Europe present a different pattern. Both the European stock market and the carbon market are sensitive to adverse news, as highlighted by the significant coefficients in the asymmetric spillover analysis. This observation implies that unfavorable news plays a role in increasing volatility in both the European stock market and the carbon market.

4.4.1 Additional test

In this subsection, we aim to correct the potential bias introduced by the COVID-19 crisis in our estimation. We have re-estimated the same model for Europe and China, considering the periods before and after the COVID-19 crisis. This analysis ensures our estimate is not biased by the COVID-19 shocks observed in the series graphs.

The results obtained from this re-estimation, presented in Table 4, highlight the consistency of our estimates with the results updated after splitting the data into two distinct periods. It is important to note that changes in the results are expected due to the change in the period considered. However, these differences do not call into question the robustness of our model. On the contrary, they reaffirm its ability to consider the effects of the COVID-19 crisis and adapt to changes in the underlying data.

The changes observed in the results reflect the dynamic nature of variables, particularly during the COVID-19 crisis. Despite these differences, our model remains reliable and robust in capturing the underlying relationships between variables, providing valuable insights into the impact of the crisis.

Furthermore, our re-estimation results provide insights into changes in market connectivity following the COVID-

19 crisis. More specifically, our observation reveals that in Europe, the interconnection between the stock market, energy markets, and the carbon market has strengthened in the post-crisis period. This suggests greater interdependence and spillover effects between these markets in the post-COVID-19 period. In contrast, an analysis of the Chinese market reveals no significant increase in connectivity. These results highlight the divergent impacts of the crisis and the different market dynamics between Europe and China.

In conclusion, the results obtained by this re-estimation in Table 4 confirm the robustness of our model and its ability to effectively incorporate the effects of the COVID-19 crisis despite the apparent differences resulting from changes in the period analyzed.

4.4.2 Robustness test

In this study, the robustness of the results is assessed by applying the Wald test, which establishes their level of credibility. The null hypothesis tested is that both $A(i,j)$ and $B(i,j)$ are equal to zero, indicating the absence of volatility from market i to market j , and, similarly, that $A(j, i)$ and $B(j,i)$ are also equal to zero, indicating the absence of volatility from market i to market j . Therefore, if all null hypotheses are rejected, we can conclude that there is significant volatility propagation between markets i and j . The results of the WALD test are presented in Table 7, which shows that the spread of volatility between the four European markets and China is almost significant. Furthermore, our results indicate that volatility between the carbon market and oil prices shifts from oil prices to the carbon market in Europe. In contrast, the opposite pattern is observed in China, consistent with the BEKK asymmetric VAR results (see Table 7).

VAR-DCC-GARCH results

The results obtained from the VAR DCC-GARCH (1,1) model are presented in Table 5. The estimated coefficients "a" and "b" show significant values, notably at the 1% level, and their aggregate aligns with the DCC model, remaining consistently below 1. The sum of "Alpha" and "Beta" coefficients is significant for all four European markets, with their sum being close to 1, indicating high sensitivity to past shocks. This suggests a high level of persistence in the volatility of returns, indicating that current volatility will likely persist.

In contrast, for China, the "Alpha" coefficient is only significant at the 1% level for the stock market, oil price, and green bond market, indicating that past shocks more influence the current volatility of the series than past volatility. This implies that recent market fluctuations considerably impact current volatility, making the series more volatile. Moreover, the non-significant "Beta1" value suggests that the impact of past volatility on current volatility is insignificant. Both "Alpha" and "Beta" coefficients are mostly significant for Chinese carbon markets, with their sum being

close to 1, indicating persistent volatility.

In Figure 6, a particularly important observation concerns the increased covariance between the European green bond market and both the carbon market and oil price. This dynamic conditional correlation, illustrated in Figures 6 and 7, underlines its importance. Notably, the dynamic conditional correlation coefficients between the European carbon market and the stock market, as well as between the European carbon market and the oil price, consistently show positive values over all periods. This trend is consistent with the findings of Zhang et al. (2017). However, a distinct trend can be seen in Europe, where the dynamic correlation coefficients between the European green bond market and the stock market mainly take on negative values.

4.5 Conclusion and policy implications

The stock market and carbon market are important for economic development, and understanding their spillover effects can help policymakers and investors make informed decisions. Stock markets represent a critical source of capital for firms, while carbon markets provide an innovative way to address environmental challenges such as climate change. China and Europe are both major players in the global economy and significantly impact the international financial system. Understanding the spillover effects between these markets can help identify potential risks and opportunities for investors and policymakers worldwide.

According to Ahmed (2023), renewable energy offers an efficient method to mitigate carbon emissions, subsequently influencing the need for carbon allowances. Fluctuations in energy and carbon prices additionally hold the potential to influence industrial production by exerting an impact on manufacturing expenses, thereby potentially affecting equity markets. Exogenous shocks such as a crisis or policy changes can modify the interrelationships among these three markets. In this context, it is essential to study the interactions between the carbon, equity, and renewable energy markets.

In addition, China and Europe have taken different approaches to developing their stock and carbon markets. By comparing these approaches and their spillover effects, we can gain insights into the effectiveness of different policy strategies and market structures. Furthermore, Carbon markets are designed to reduce greenhouse gas emissions, and understanding their spillover effects can help to assess their effectiveness in achieving this goal. By comparing the spillover effects of carbon markets in China and Europe, we can identify best practices and areas for improvement to promote more sustainable economic growth. This paper uses a VAR BEKK GARCH (1,1) model with asymmetry to study the non-linear impacts and volatility transmission between energy, carbon, and stock markets in Europe and China. Additionally, a DCC GARCH (1,1) model was employed to depict the changing correlation

dynamics over time among the markets.

According to our results, there is a high transmission of volatility between stock markets and the carbon market, as well as between oil prices and green bond markets. China's carbon market appears to be central in transmitting volatility, establishing a significant connection between the country's stock market, oil prices, and green bond market. Furthermore, our analysis indicates no direct connectedness between the oil price and the green bond market in Europe. The connectedness between the stock market, carbon market, and green bond can be explained by the degree of integration and maturity of these markets in a particular region. In Europe, these markets have been developing and integrating over a longer period, leading to a more long-term relationship. This means that changes in one market tend to have a more gradual and sustained effect on the other markets over time.

On the other hand, in China, these markets are still relatively new and less developed, resulting in a more short-term relationship between them. This means that changes in one market can have a more immediate and volatile impact on the others. Moreover, the regulatory frameworks and policies related to these markets also influence the degree of connectedness. In Europe, more established policies and regulations encourage and support sustainable investments, further strengthening the long-term relationship between the markets. In contrast, China has focused more on short-term economic growth, which may have led to a less mature and more volatile market relationship. Looking at the asymmetric effect of a single market in China, it's clear that positive news dominates the volatility of the carbon and green bond markets. This implies that when positive news emerges, it intensifies the volatility in these markets, reflecting investors' risk aversion mentality. On the other hand, good news in the stock market results in reduced volatility as it restrains the inherent risks in the market. This suggests that investors may be overestimating the level of uncertainty in the Chinese stock market. In contrast, The results concerning the asymmetric spread of volatility in Europe indicate the absence of an asymmetric impact on the carbon, stock, and green bond markets.

These findings suggest that there are complex relationships between these markets and that investors are considering multiple factors when making investment decisions. In addition, the significant values of $dcca1$ and $dccb1$ suggest that the assets in the model are related and that their correlation changes over time, and investors may use this information to construct more accurate portfolio models or risk management strategies. Traders and related businesses face uncertainties about the future due to various policies, resulting in low causality between the two different markets. The Chinese carbon market initially displayed an increasing causal influence on stock markets from its inception in December 2013 until December 2017. Nevertheless, from 2018, the carbon market's influence on financial markets gradually declined, with stock markets linked to energy-intensive industries having a greater impact on the carbon market. This suggests that investors and market participants must adopt a dynamic approach, continually adjusting their analysis and drawing appropriate conclusions to inform investment decisions. By harnes-

sing information from the carbon emissions trading market, investors can effectively forecast equity returns in China in the short and long term.

Finally, China's government has made efforts to accelerate the adoption of carbon markets in recent years to achieve environmental objectives. Closely observing the interrelationships involving the carbon market, stock market, and green bond market could yield benefits for the government. As these markets exhibit asymmetric spillover effects, positive news in one market may have a domino effect on the volatility of the other markets. Furthermore, given the strong correlation between the Chinese carbon market and oil prices, it may be prudent for the government to consider adopting measures to mitigate the influence of oil price fluctuations on the carbon market. Moreover, it may be worthwhile for the Chinese government to study the European carbon market and learn from their policies and practices to strengthen their own carbon market.

From a more general perspective, the results of this study provide a better understanding of the interdependence between the carbon market and other markets in Europe and China. These findings are essential for policy-makers and investors, as they underline the need for a solid strategy in the fight against climate change, which considers the possible spillover effects of energy and financial markets on the carbon market. In conclusion, this study underlines the importance of further exploration in this field to formulate effective policy measures to mitigate the impact of climate change and ensure a sustainable future for our world.

Appendices

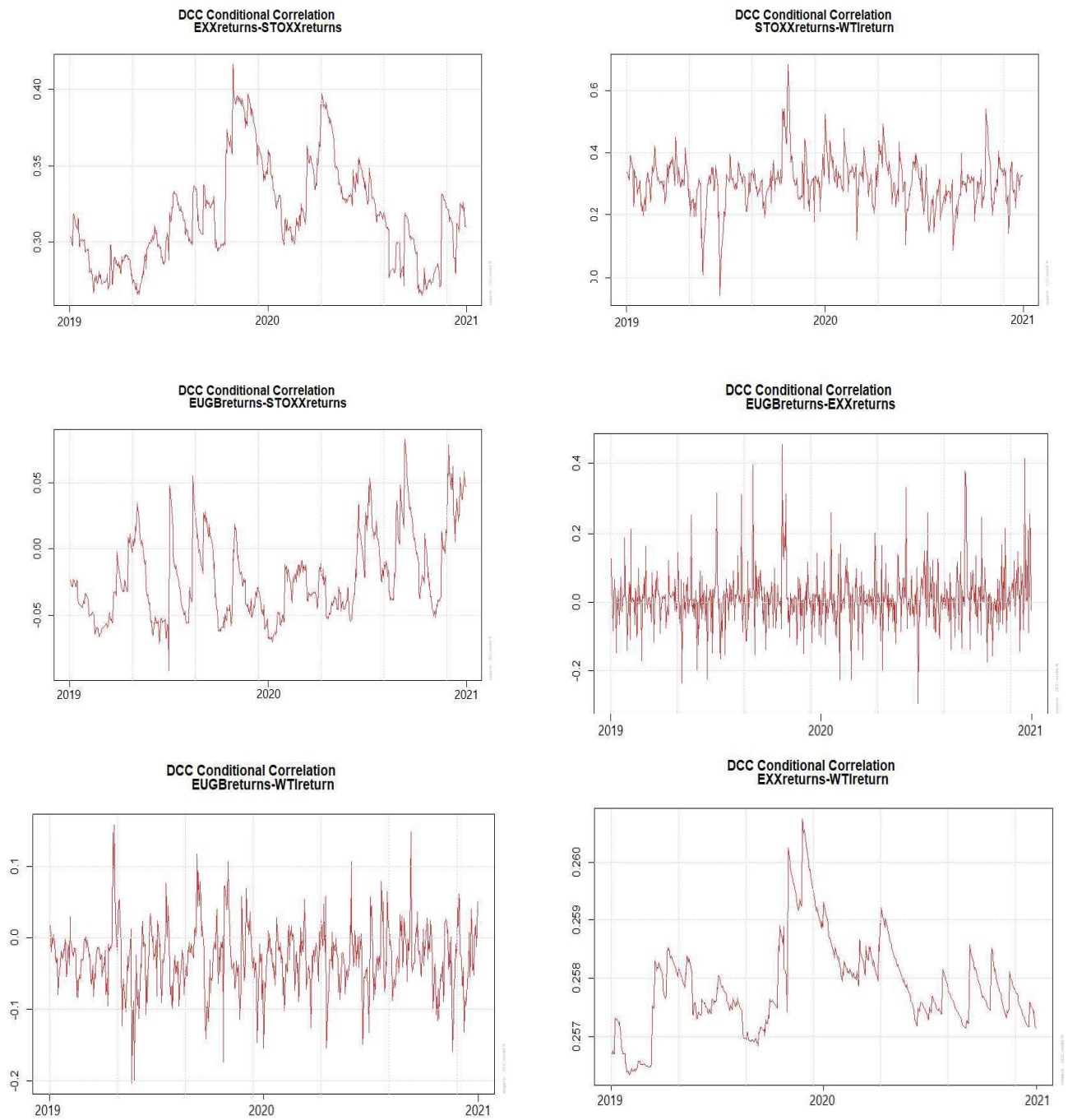


FIGURE 4.3 – Dynamic conditional correlation between european markets

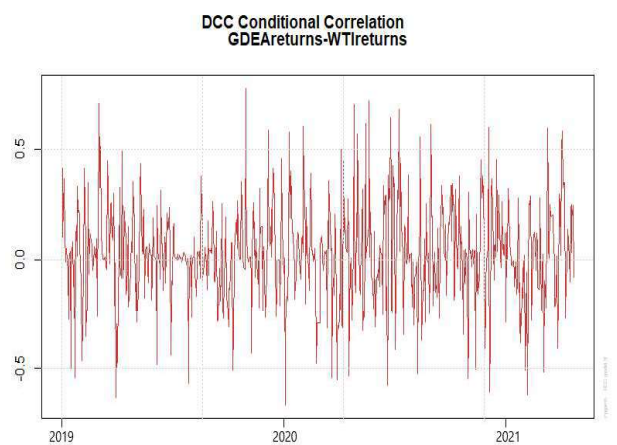
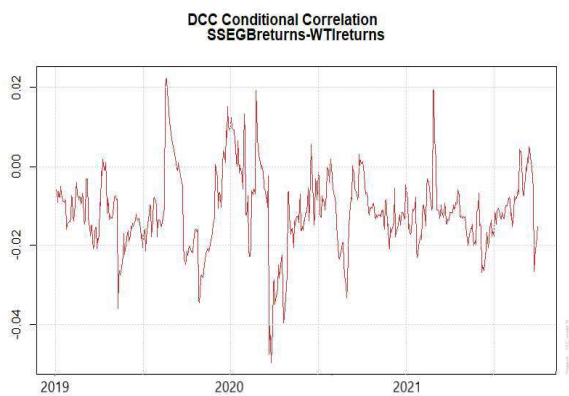
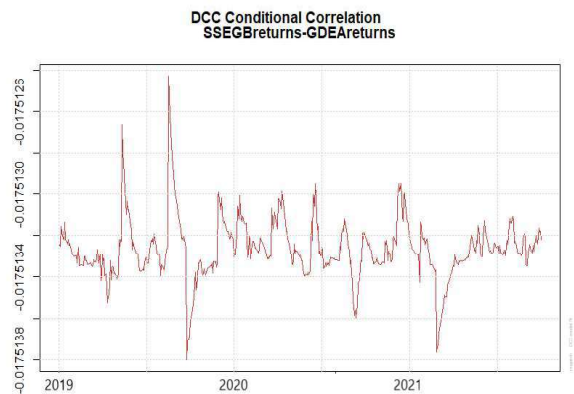
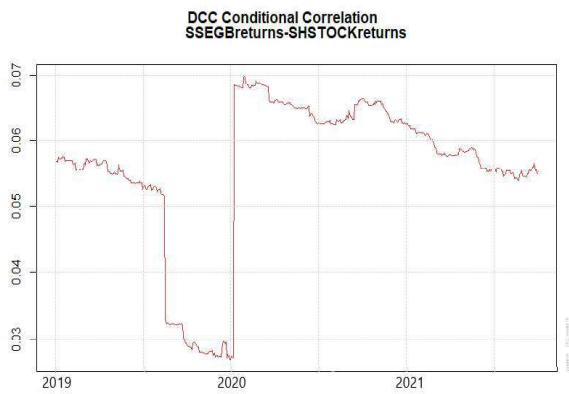
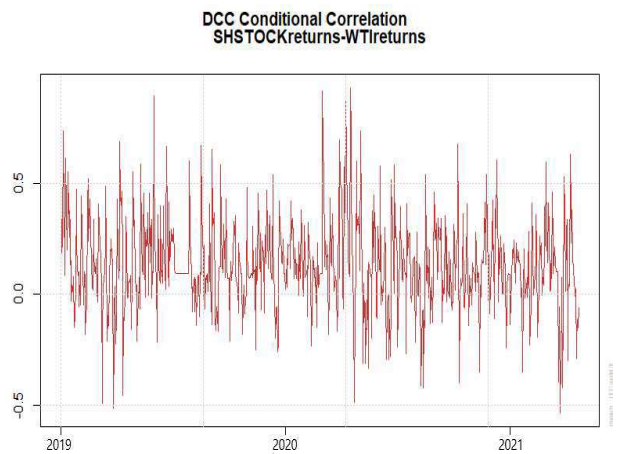
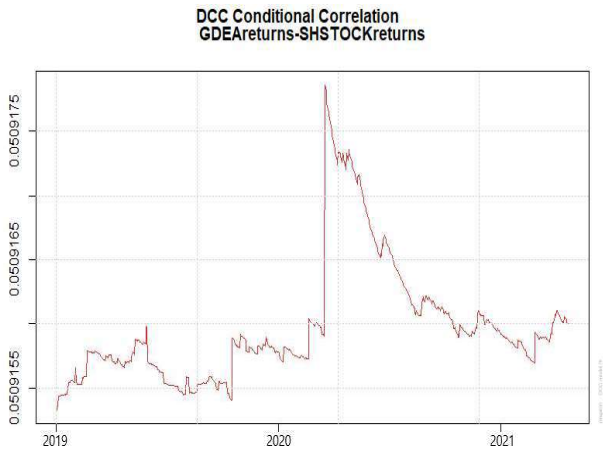


FIGURE 4.4 – Dynamic conditional correlation between Chinese markets

TABLE 4.4 – The Asymmetric VAR-BEKK-GARCH estimation results

	China			Europe		
	Coefficient	T-statistic	P-value	Coefficient	T-statistic	P-value
C (1,1)	0.0079	4.3347	0.0000	0.0009	1.1561	0.2477
C (2,1)	0.0028	1.9332	0.0532	0.0063	2.3242	0.0201
C (2,2)	0.0039	3.2451	0.0012	0.0028	0.5357	0.5922
C (3,1)	-0.0029	-0.9782	0.3280	-0.0013	-0.3319	0.7400
C (3,2)	0.0039	1.1073	0.2682	-0.0025	-0.8183	0.4132
C (3,3)	0.0025	0.4458	0.6557	0.0001	0.0443	0.9647
C (4,1)	0.0000	-0.3677	0.7131	0.0002	0.1520	0.8792
C (4,2)	-0.0001	-0.4771	0.6333	0.0017	0.7666	0.4433
C (4,3)	0.0001	1.4816	0.1385	-0.0004	-0.2200	0.8258
C (4,4)	-0.0001	-0.3203	0.7488	0.0009	0.2553	0.7985
A (1,1)	-0.1753	-1.5369	0.1243	-0.1842	-3.8784	0.0001
A (1,2)	-0.0143	-0.9291	0.3528	-0.3074	-3.4556	0.0005
A (1,3)	0.0047	0.1502	0.8806	-0.6230	-4.7437	0.0000
A (1,4)	-0.0045	-4.5468	0.0000	0.0660	3.8183	0.0001
A (2,1)	1.1019	3.0153	0.0026	0.0160	1.2405	0.2148
A (2,2)	-0.2813	-2.7990	0.0051	0.1698	5.2469	0.0000
A (2,3)	0.0307	0.6093	0.5423	-0.0619	-1.7106	0.0872
A (2,4)	0.0073	2.6650	0.0077	0.0048	0.8039	0.4215
A (3,1)	0.3683	3.1347	0.0017	0.0259	1.6524	0.0984
A (3,2)	0.0374	1.8178	0.0691	0.0737	2.7668	0.0057
A (3,3)	0.1056	1.6354	0.1020	0.2693	4.5112	0.0000
A (3,4)	-0.0018	-3.3791	0.0007	0.0272	3.5454	0.0004
A (4,1)	84.9347	2.9631	0.0030	0.3160	2.0745	0.0380
A (4,2)	8.3724	3.2840	0.0010	0.2081	0.6563	0.5116
A (4,3)	-2.6174	-1.7569	0.0789	0.3633	1.0099	0.3125
A (4,4)	-0.0382	-0.5518	0.5811	0.4619	9.1206	0.0000
B (1,1)	-0.0363	-1.1119	0.2662	0.9446	34.8264	0.0000
B (1,2)	0.0600	2.1759	0.0296	0.1010	1.7671	0.0772
B (1,3)	0.0169	0.6352	0.5253	-0.0505	-0.6343	0.5259
B (1,4)	0.0060	2.7625	0.0057	-0.0341	-1.6159	0.1061
B (2,1)	0.0175	0.2304	0.8178	-0.0312	-4.9423	0.0000
B (2,2)	-0.8689	-26.9691	0.0000	0.9112	37.5681	0.0000
B (2,3)	-0.0585	-0.4151	0.6781	0.0202	0.6775	0.4981
B (2,4)	0.0010	0.2138	0.8307	-0.0174	-1.8354	0.0665
B (3,1)	0.1602	3.1844	0.0015	-0.0184	-2.9129	0.0036
B (3,2)	0.0185	0.5778	0.5634	-0.0261	-1.2547	0.2096
B (3,3)	0.9179	19.2311	0.0000	0.8429	29.8110	0.0000
B (3,4)	-0.0013	-2.4865	0.0129	0.0008	0.0888	0.9293
B (4,1)	-0.3687	-0.1500	0.8808	-0.5396	-1.9839	0.0473
B (4,2)	0.4879	0.1840	0.8540	-1.5365	-2.7461	0.0060
B (4,3)	0.8691	0.5837	0.5594	-1.5429	-2.2825	0.0225
B (4,4)	0.7302	14.9131	0.0000	-0.3433	-2.9190	0.0035
D (1,1)	-0.5593	-4.9152	0.0000	0.3431	3.6626	0.0002
D (1,2)	-0.0137	-1.5784	0.1145	0.0401	0.3369	0.7362
D (1,3)	0.0034	0.1498	0.8810	0.1075	0.4349	0.6636
D (1,4)	-0.0032	-2.1346	0.0328	0.0078	0.4815	0.6301
D (2,1)	0.0655	0.2567	0.7974	0.0254	0.9342	0.3502
D (2,2)	0.3698	2.9079	0.0036	0.1548	2.0955	0.0361
D (2,3)	-0.0300	-0.1319	0.8950	-0.0947	-1.3403	0.1801
D (2,4)	0.0022	0.5682	0.5699	-0.0049	-0.6851	0.4933
D (3,1)	0.0236	0.5022	0.6156	0.0345	1.4028	0.1607
D (3,2)	-0.0199	-1.4258	0.1539	-0.0029	-0.0805	0.9359
D (3,3)	-0.4574	-2.9537	0.0031	0.5151	5.6527	0.0000
D (3,4)	-0.0004	-0.4965	0.6196	-0.0122	-1.1545	0.2483
D (4,1)	1.3536	0.3083	0.7578	-0.2978	-1.7616	0.0781
D (4,2)	-0.4829	-0.3767	0.7064	0.2687	0.7842	0.4330
D (4,3)	-1.7839	-0.6960	0.4864	1.3333	2.0688	0.0386
D (4,4)	0.3869	4.7056	0.0000	0.0801	0.7127	0.4760

TABLE 4.5 – DCC-GARCH estimation results

	China			Europe		
	Coefficient	T-statistic	P-value	Coefficient	T-statistic	P-value
WTLreturns .mu	-0.0001	-0.0842	0.9329	0.0023	4.1393	0.0000
WTLreturns .ar1	0.4480	4.1795	0.0000	0.5484	3.5409	0.0004
WTLreturns .mat	-0.1347	-1.4768	0.1397	-0.6069	-4.2239	0.0000
WTLreturns .omega	0.0003	4.9300	0.0000	0.0000	2.3191	0.0204
WTLreturns .alpha1	0.9681	5.7358	0.0000	0.1377	2.8711	0.0041
WTLreturns .beta1	0.0309	0.6624	0.5077	0.8322	18.1989	0.0000
WTLreturns .shape	3.0507	12.9459	0.0000	3.4982	7.1015	0.0000
SHSTOCKreturns .mu	0.0015	2.2707	0.0232	0.0010	6.8497	0.0000
SHSTOCKreturns .ar1	0.3799	5.3011	0.0000	0.8939	28.9844	0.0000
SHSTOCKreturns .mat	-0.1345	-2.2261	0.0260	-0.9503	-63.2355	0.0000
SHSTOCKreturns .omega	0.0002	3.1159	0.0018	0.0000	0.7394	0.4597
SHSTOCKreturns .alpha1	0.8654	2.1431	0.0321	0.1955	3.9500	0.0001
SHSTOCKreturns .beta1	0.0000	0.0000	1.0000	0.8035	11.7937	0.0000
SHSTOCKreturns .shape	2.8728	5.5075	0.0000	3.3428	7.2321	0.0000
GDEAReturns .mu	0.0003	0.9215	0.3568	0.0015	1.8038	0.0713
GDEAReturns .ar1	-0.8494	-7.2867	0.0000	-0.6879	-5.3729	0.0000
GDEAReturns .mat	0.8275	6.4687	0.0000	0.5997	4.2993	0.0000
GDEAReturns .omega	0.0000	3.0588	0.0022	0.0000	1.5179	0.1290
GDEAReturns .alpha1	0.8641	7.1343	0.0000	0.0623	2.3667	0.0179
GDEAReturns .beta1	0.1349	1.6597	0.0970	0.8874	17.8383	0.0000
GDEAReturns .shape	4.0748	9.8915	0.0000	5.6536	5.4451	0.0000
SSEGBReturns .mu	0.0002	7.2974	0.0000	0.0002	3.0722	0.0021
SSEGBReturns .ar1	0.8247	23.0925	0.0000	0.0879	0.5130	0.6079
SSEGBReturns .mat	-0.5746	-10.6964	0.0000	-0.2702	-1.6546	0.0980
SSEGBReturns .omega	0.0000	0.0121	0.9904	0.0000	1.3398	0.1803
SSEGBReturns .alpha1	0.0593	1.4174	0.1564	0.1212	2.9468	0.0032
SSEGBReturns .beta1	0.9039	19.4856	0.0000	0.7845	22.5577	0.0000
SSEGBReturns .shape	4.1723	3.5196	0.0004	5.2449	3.2059	0.0013
Joint decal	0.0103	0.9659	0.3341	0.0297	2.0680	0.0386
Joint decb1	0.9781	34.1679	0.0000	0.7484	7.4603	0.0000
Joint decg1	0.0103	0.5156	0.6061	0.0063	0.2282	0.8195
Joint mshape	4.0071	14.2641	0.0000	5.0404	11.9704	0.0000

TABLE 4.6 – Pre and Post Covid-19 estimation

Variable	China				Europe				
	Pre-crisis		Post-crisis		Pre-crisis		Post -crisis		
	Coefficient	P-value	Coefficient	P-value	Coefficient	P-value	Coefficient	P-value	
C(1,1)	0.0099	0.0000	0.0035	0.0257	C(1,1)	0.0022	0.2284	0.0030	0.0002
C(2,1)	0.0007	0.7720	0.0028	0.5533	C(2,1)	-0.0099	0.4988	-0.0115	0.0000
C(2,2)	0.0137	0.0000	0.0057	0.0502	C(2,2)	0.0118	0.2699	0.0018	0.5848
C(3,1)	0.0062	0.0684	-0.0061	0.0346	C(3,1)	0.0017	0.5286	-0.0031	0.1050
C(3,2)	0.0002	0.9731	-0.0021	0.7101	C(3,2)	0.0027	0.1421	0.0007	0.6710
C(3,3)	0.0026	0.6577	0.0000	1.0000	C(3,3)	0.0000	0.9990	0.0012	0.4522
C(4,1)	0.0000	0.3901	0.0001	0.2782	C(4,1)	0.0007	0.1096	0.0006	0.0769
C(4,2)	0.0000	0.8577	0.0000	0.6051	C(4,2)	0.0010	0.1836	0.0014	0.2112
C(4,3)	0.0001	0.4736	0.0000	0.9999	C(4,3)	0.0000	0.9975	0.0013	0.2295
C(4,4)	0.0000	0.9999	0.0000	0.9999	C(4,4)	0.0000	0.9997	-0.0001	0.9693
A(1,1)	-0.0281	0.9461	0.3353	0.0000	A(1,1)	0.3867	0.0000	-0.2508	0.0038
A(1,2)	-0.0551	0.6746	-0.0106	0.8439	A(1,2)	0.3649	0.5621	-0.9783	0.0007
A(1,3)	-0.0823	0.7974	-0.0886	0.2150	A(1,3)	0.2170	0.6063	-0.1443	0.5064
A(1,4)	-0.0055	0.0924	0.0008	0.4632	A(1,4)	0.0130	0.6407	0.0287	0.2811
A(2,1)	-0.1269	0.1874	0.0501	0.6434	A(2,1)	-0.0015	0.9770	0.0047	0.8635
A(2,2)	0.0834	0.7168	0.7391	0.0000	A(2,2)	0.3911	0.0010	0.2584	0.0005
A(2,3)	-0.0774	0.2812	0.0434	0.7243	A(2,3)	-0.0314	0.3551	0.0468	0.3547
A(2,4)	0.0244	0.0000	0.0017	0.2438	A(2,4)	-0.0114	0.3998	-0.0236	0.0012
A(3,1)	0.0542	0.3604	-0.1011	0.0004	A(3,1)	0.0174	0.3611	0.0201	0.4719
A(3,2)	0.1325	0.0593	0.0114	0.7554	A(3,2)	-0.1467	0.1455	-0.0601	0.6509
A(3,3)	0.1898	0.0357	0.2644	0.0003	A(3,3)	0.4692	0.0003	0.1429	0.2685
A(3,4)	0.0036	0.0003	0.0025	0.0006	A(3,4)	-0.0077	0.6146	-0.0269	0.0518
A(4,1)	-0.4296	0.8508	-0.7892	0.8585	A(4,1)	0.1875	0.6280	-0.0865	0.7940
A(4,2)	-1.9599	0.7305	-0.3126	0.9517	A(4,2)	-0.0782	0.9486	-3.7092	0.0000
A(4,3)	3.0348	0.4323	7.5678	0.2781	A(4,3)	0.9711	0.2078	0.3030	0.5036
A(4,4)	0.2189	0.0216	0.0554	0.6525	A(4,4)	0.6383	0.0003	-0.3522	0.0001
B(1,1)	0.1417	0.3847	-0.8014	0.0000	B(1,1)	0.6194	0.0013	0.6128	0.0001
B(1,2)	0.0633	0.7019	0.1159	0.5306	B(1,2)	1.0306	0.0105	1.9706	0.0000
B(1,3)	0.6617	0.0229	-0.1985	0.4236	B(1,3)	1.6106	0.0370	1.1396	0.0001
B(1,4)	0.0036	0.2330	-0.0051	0.0193	B(1,4)	-0.0988	0.1003	-0.0242	0.5460
B(2,1)	-0.1130	0.4582	0.2073	0.3023	B(2,1)	0.0862	0.4431	0.1001	0.0654
B(2,2)	0.3140	0.3269	0.2783	0.0149	B(2,2)	0.4319	0.0013	-0.0398	0.8753
B(2,3)	0.1323	0.5458	0.1083	0.3634	B(2,3)	-0.3758	0.0505	-0.3585	0.0085
B(2,4)	-0.0095	0.0017	0.0080	0.0327	B(2,4)	0.0019	0.9526	-0.0227	0.1065
B(3,1)	-0.1148	0.4237	-0.0401	0.8024	B(3,1)	0.0139	0.7832	0.0197	0.7130
B(3,2)	-0.1258	0.4006	0.0869	0.2579	B(3,2)	-0.4679	0.1606	-0.4736	0.0347
B(3,3)	0.6712	0.0000	0.7869	0.0000	B(3,3)	-0.3647	0.1269	0.5031	0.0011
B(3,4)	-0.0016	0.5357	-0.0018	0.6009	B(3,4)	0.0237	0.7841	0.0471	0.0016
B(4,1)	-3.4522	0.2848	22.2968	0.0000	B(4,1)	0.2508	0.4856	-0.0099	0.9826
B(4,2)	9.0993	0.1495	6.5452	0.5270	B(4,2)	-2.0029	0.5433	-2.5463	0.0440
B(4,3)	16.3752	0.0770	-0.6491	0.9700	B(4,3)	-2.6098	0.0316	2.2615	0.0136
B(4,4)	0.0695	0.3278	-0.7199	0.0000	B(4,4)	0.0664	0.9265	-0.4430	0.0000
D(1,1)	-0.7457	0.0000	-0.1420	0.2387	D(1,1)	0.7407	0.0002	0.3735	0.0011
D(1,2)	-0.0745	0.6726	-0.0481	0.5092	D(1,2)	-0.6420	0.3234	-0.6731	0.0401
D(1,3)	0.0932	0.7594	0.1684	0.0778	D(1,3)	-0.0673	0.9055	-0.8892	0.0001
D(1,4)	-0.0031	0.4882	-0.0020	0.2676	D(1,4)	-0.0754	0.1232	0.0551	0.2767
D(2,1)	-0.0049	0.9514	-0.2034	0.1743	D(2,1)	-0.0987	0.0501	0.1364	0.0011
D(2,2)	-0.7523	0.0000	-0.50567	0.0567	D(2,2)	-0.1286	0.7098	0.2838	0.0169
D(2,3)	0.2400	0.3323	-0.5562	0.1583	D(2,3)	-0.0311	0.6248	0.0888	0.2678
D(2,4)	-0.0014	0.8158	-0.0066	0.0038	D(2,4)	0.0058	0.6351	0.0132	0.2750
D(3,1)	0.2736	0.0295	-0.0132	0.7948	D(3,1)	-0.0138	0.8118	0.0122	0.8213
D(3,2)	-0.0350	0.7443	0.0805	0.1102	D(3,2)	0.4164	0.0006	0.0018	0.9868
D(3,3)	-0.4202	0.1855	-0.4327	0.0016	D(3,3)	0.2972	0.3500	0.4417	0.0001
D(3,4)	0.0021	0.4121	0.0049	0.0001	D(3,4)	0.0440	0.0481	0.0170	0.4309
D(4,1)	9.3873	0.0324	5.9294	0.3329	D(4,1)	-0.4920	0.4077	0.3053	0.2880
D(4,2)	18.4022	0.0285	-3.4972	0.7779	D(4,2)	-0.4623	0.8415	0.7150	0.4786
D(4,3)	5.3685	0.2821	-1.9176	0.7333	D(4,3)	0.3643	0.7937	1.4142	0.0682
D(4,4)	-0.4616	0.0304	0.4240	0.0000	D(4,4)	0.5838	0.0039	-0.1734	0.2185

TABLE 4.7 – Results of WALD test

Market A	Market B	Hypothesis test 1 : H0 : no volatility spillover from market A to market B	Hypothesis test 2 : H0 : no volatility spillover from market B to market A	China	Europe
Stock market	Carbon market	H0 : A(1,2) = B(1,2) = 0	H0 : A(2,1) = B(2,1) = 0	Wald test1 : 243.8847*** Wald test 2 : 45.8027***	Wald test1 : 28.6437*** Wald test 2 : 5.4976*
Stock market	Green bond	H0 : A(1,4) = B(1,4) = 0	H0 : A(4,1) = B(4,1) = 0	Wald test1 : 156.1010*** Wald test 2 : 417.4163***	Wald test1 : 23.4173*** Wald test 2 : 4.3447
Stock market	Oil price	H0 : A(1,3) = B(1,3) = 0	H0 : A(3,1) = B(3,1) = 0	Wald test1 : 59.2356*** Wald test 2 : 11.3407***	Wald test1 : 18.2155*** Wald test 2 : 23.1241***
Oil price	Carbon market	H0 : A(3,2) = B(3,2) = 0	H0 : A(3,2) = B(3,2) = 0	Wald test1 : 243.8847*** Wald test 2 : 1.9502	Wald test1 : 18.2155*** Wald test 2 : 3.1187
Oil price	Green bond	H0 : A(3,4) = B(3,4) = 0	H0 : A(4,3) = B(4,3) = 0	Wald test1 : 12.5817** Wald test 2 : 157.6005***	Wald test1 : 5.7708* Wald test 2 : 7.7543*
Carbon market	Green bond	H0 : A(4,2) = B(4,2) = 0	H0 : A(2,4) = B(2,4) = 0	Wald test1 : 5.340840* Wald test 2 : 118.1620***	Wald test1 : 9.7581*** Wald test 2 : 5.4505*

Note : ***, **, * represent 1%, 5% and 10% significance respectively

Chapitre 5

The effects of decomposed oil-price shocks on carbon markets

Abstract ¹

The carbon market represents a central mechanism in the context of climate change mitigation, while oil shocks have a significant influence on global economic dynamics. Motivated by the need to understand the interactions between oil shocks and carbon markets, we use Ready's (2018) oil price decomposition method, which divides oil shocks into supply, demand, and oil company financial risk. Using a structural vector autoregression (SVAR) model, we study the impact of these shocks on the European and Chinese carbon markets, considering major events such as the war between Russia and Ukraine, the COVID-19 crisis, and the oil crash. We refine this model using a structural vector autoregressive model with time-varying stochastic volatility (TVP-SVAR-SV) to capture the evolution of relationships. Empirical results reveal different impacts in the two regions, although the European carbon market remains stable, reacting positively to fluctuations in oil demand and supply but negatively to risk shocks. The Chinese carbon market reacts strongly to oil demand shocks due to its high dependence on oil and its strong industrial presence. Given that the origin of shocks to carbon market efficiency appears to be a critical element, these results have implications for risk management strategies and the achievement of emissions reductions.

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5.1 Introduction

The issue of climate change and global warming, caused by greenhouse gas emissions, has garnered significant global attention. Carbon emissions trading markets (CETs) have been identified as an effective means of promoting low-carbon economic development and reducing greenhouse gas emissions (Wen et al., 2020; Zhao et al., 2020). Meanwhile, crude oil consumption, as a fundamental input for economic and social activities, impacts carbon emissions through various channels, such as energy supply for production and transportation, which affect the dynamics of the carbon market (Hammoudeh et al., 2014; Dong et al., 2021; Zhang et al., 2021; Zheng et al., 2021; Lau et al., 2023). However, few studies have considered that oil price fluctuations caused by different shocks may have varying consequences. For instance, an increase in oil prices may result from an increase in demand or a reduction in supply. Although the outcome may be the same, the reason behind it may have different effects on oil consumption, resulting in differences in carbon emissions. Therefore, it is crucial to examine how carbon allowance prices may be affected by different oil price incentives. Given the strong impact of oil prices on the CET market found in previous studies, it is necessary to explore the relationship between oil shocks and carbon allowance prices.

Various methods have been used to classify oil price shocks from different sources as supply- or demand-driven. One approach is to use exogenous instruments for oil price changes, such as events affecting oil production, as proposed by Hamilton (2003). Other studies have utilized data on oil production to identify various shocks, such as the decomposition method developed by Kilian (2009) and Kilian and Park (2009). However, Kilian's method has been criticized for its inability to capture slow day-to-day changes in oil prices and to distinguish between oil-specific demand shocks driven by concerns about future oil supply or changes in the aggregate demand for oil. To address these limitations, Ready (2018) developed a decomposition method that identifies oil price changes driven by oil supply, demand, and risk shocks. This method uses daily data, which allows for more effective information gathering and improved results compared to previous methods.

Although the importance of studying the potentially varied impact of different oil shocks on the interaction between oil and carbon markets is widely recognized, research in this area remains limited. It is understood that an increase in oil prices can result from an increase in demand or a decrease in supply and that market conditions can also influence decision-making, thereby altering the dynamics of the crude oil market and affecting carbon prices (Zheng et al., 2021). Furthermore, the relationship between oil and carbon markets can vary across time and market conditions, revealing the asymmetry of the link across the distribution of data and at different scales (Hammoudeh et al., 2014; Maghyereh and Abdoh, 2021).

The existing literature on carbon market dynamics has mainly focused on the price channel of return and volatility

(Dou et al., 2021). This approach assumes that the market is efficient and that prices reflect unbiased information for resource allocation. However, in reality, the market can be inefficient due to various frictions, meaning that current price dynamics might not accurately reflect available price information (Daskalakis and Markellos, 2021). Relying solely on price information can result in unreliable inferences that fail to capture the true dynamics of the carbon market. To provide a more accurate demonstration of the market dynamics, it is important to consider the degree of market inefficiency, which represents the closeness of the actual market status to an efficient condition (Duan et al., 2021).

We investigate the relationship between oil price shocks and carbon allowance prices by examining the link between oil and carbon allowances. Prior research by Hammoudeh et al. (2015) suggests that crude oil prices have a long-term negative and asymmetric effect on carbon allowance prices. Similarly, Dutta (2018) finds evidence of asymmetric impact of The CBOE Crude Oil ETF Volatility Index on the EU Allowance market. Nonlinearity and asymmetry in price interactions are important due to the complexity of the economic system governing the data-generating process in the oil shocks and carbon emission markets. Factors such as extreme events, geopolitical tensions, market turbulence, extreme weather, financial market sophistication, and regulation multiplicity can all contribute to an asymmetric relationship between oil shocks and carbon allowance prices, implying a nonlinear relationship between them. Hence, we use the structural VAR (SVAR) model methodology to disentangle oil price shocks. To our knowledge, no previous studies have examined and compared the nonlinear and asymmetric relationship between the CET and EUA markets and oil shocks.

Our decision to select China as our research subject is based on several reasons. Firstly, China is not only the biggest developing country but also the world's largest carbon emitter (Liu, 2016; Zheng et al., 2019). China's national CET market covering over 4 billion tons of carbon emissions equivalent, it is more than twice that of Europe, making it the world's largest CET system (Wen et al., 2020d). Thus, China's efforts towards emission reduction have a significant worldwide impact. Secondly, China's rapid industrialization and urbanization processes have led to a surge in the consumption and import of crude oil, where China ranks as the top crude oil importer according to data from the General Administration of Customs (GAC). Additionally, crude oil import dependency in China has been growing yearly, reaching 72.7% in 2019 alone. As a significant source of carbon dioxide emissions, crude oil has become increasingly linked with China's CET markets. Some studies have examined the relationship between the oil market and carbon emissions in China's CET markets (Sun et al., 2018; Zhang and Zhang, 2016). Therefore, international oil shocks will likely impact China's CET markets due to its heavy reliance on oil imports. However, prior research has neglected the effect of oil shocks from different sources on China's CET market, even though these shocks can affect the price of carbon allowances. By understanding these differences, we can establish stable CET markets.

In addition to focusing on China's CET market, we also select the European Union Emissions Trading Scheme (EU ETS) as a comparison due to its significance as the largest and first-established carbon market worldwide. The EU ETS has operated since 2005 and has promoted low-carbon transitions across the European Union. Furthermore, research has shown that the ETS has effectively reduced emissions at a minimum economic cost (Zhao et al., 2021). By comparing the effects of oil shocks on China's CET market and the EU ETS, we can gain a better understanding of the similarities and differences between these two important carbon markets and their responses to external shocks.

5.2 Literature review

It is essential to consider supply and demand shocks when studying the impact of oil prices on macroeconomic components. Oil price fluctuations can affect economic activity in different ways depending on the source of these fluctuations (Killian (2009)). A supply shock can occur when oil supplies fall due to geopolitical conflicts, labor shortages, or natural disasters. Oil prices can then rise, reducing production in sectors heavily dependent on energy, such as manufacturing, transport, or agriculture. Companies may pass these higher costs to consumers, leading to higher inflation. Households may also reduce consumption, leading to a contraction in economic activity.

On the other hand, a demand shock can occur when demand for oil increases or decreases due to factors such as economic growth, environmental policies, or changes in consumer behavior. It can also affect economic activity in different ways. An increase in oil demand can stimulate economic activity in energy-dependent sectors, while a decrease in oil demand can lead to reduced production.

Thus, by considering supply and demand shocks in the study of the impact of oil prices on macroeconomic and financial components, it is possible to identify the transmission channels of oil price fluctuations in the economy, which can help formulate appropriate economic policies to mitigate the negative effects of oil shocks on real activity and the environment. The economic theory that explains the impact of supply and demand shocks on oil prices and their influence on economic activity is widely studied in economics and has been proposed by several authors (Hubbert, 1950 ; Hamilton, 1980 ; Kilian, 2009). Recently, a growing number of researchers have been investigating the relationship between decomposed oil prices and carbon prices. Table 1 below summarizes some of the literature on the effects of oil price shocks on carbon markets.

TABLE 5.1 – Literature Review Summary Table

Authors	Region\Country	Period study	Methodology	Major findings
Jalil and Feridun (2011)	China	From 1953 to 2006.	ARDL model	<p>Carbon emissions are determined by income, energy consumption and trade openness in the long term. In the second phase of the EU ETS, the main determinants of the carbon price are oil prices, stock market indices and the transition from gas to coal prices. The correlations between electricity, gas, coal and oil prices and carbon prices have been relatively high. An increase in the price of crude oil leads to a substantial decrease in the carbon price when the latter is very high.</p> <p>There is a significant one-way volatility transfer from the coal market to the carbon market and from the carbon market to the natural gas market, while there is no significant volatility transfer between the carbon market and the Brent oil market.</p> <p>The impact of the prices of fossil fuels such as coal, oil and gas is lagged, affecting the price of carbon in the medium and long term respectively.</p> <p>The shock in oil supply and oil demand increases the price of carbon allowances, while the oil risk shock results in a reduction in carbon allowances.</p> <p>Carbon emission trading price is significantly related to some energy intense sectors and financial sector stock market.</p> <p>The carbon market exhibits stable long-term characteristics in reducing energy intensity but shows instability when improving emission efficiency.</p> <p>The role of oil shocks in impacting the degree of carbon market inefficiency varies according to the source of the oil shock</p>
Crediti et al. (2012)	Europe	From June 24, 2005 to December 20, 2010.	Cointegration techniques	
Aatola et al. (2013)	Europe	From 2005 to 2010.	OLS, IV and VAR models	
Hammoudeh et al. (2014)	United States	From July 2006 to November 2013.	Quantile regression framework	
Zhang and Sun (2016)	Europe	From January 2, 2008 to September 30, 2014.	DCC GARCH and BEKK GARCH	
Zhu et al. (2019)	Europe	from 2009 to 2016.	Cointegration techniques, error correction model and Newey–West estimator	
Wen et al. (2020)	China	From June 18, 2013, to June 15, 2020.	NARDL model	
Zheng et al. (2021)	China	From August 9, 2013 to April 19, 2019.	NARDL model	
Zhou et al. (2022)	China	From 2000 to 2017 .	Difference-in-differences model	
Ren et al. (2022)	Europe	From January 01, 2014 to April 16, 2021 .	Quantile coherency approach	

5.3 Methodology

Based on the analysis mentioned earlier, it is crucial to investigate the transmission of oil price shocks (such as oil supply, demand and risk shocks) to carbon prices in a structural dynamic multivariate framework. It is also essential to account for possible changes in the underlying economic relationship over time by allowing our dynamic specification to be time-varying. Therefore, a two-stage estimation strategy is constructed to conduct our empirical methodology. The econometric framework used in this study consists of three different approaches. First, the classification strategy proposed by Ready (2018) is applied to decompose oil price variations using the SVAR approach. Second, we proceed to build a TVP-SVAR model with stochastic volatility to assess the time-varying responses of carbon market returns to oil shocks.

5.3.1 Structural VAR framework

As mentioned, the decomposition method by Kilian (2009) of oil price decomposition has several areas for improvement. In line with research by Demirer et al. (2020), who noted, that the method tends to overemphasize oil-specific demand shocks, often disregarding the importance of supply shocks. To address these limitations, Ready (2018) employs prices of traded financial assets. He characterizes demand shocks as the segment of returns on a global stock index of oil-producing companies, independent of the changes in the VIX volatility index. The fundamental assumption is that these companies will be subject to the influence of demand shocks while possessing an inbuilt mechanism to mitigate the effects of supply shocks. This assumption is supported by introducing a simplified model, whose underlying logic can be resumed as follows. An increase in oil prices attributed to higher demand should allow producers to sell a minimum volume of oil at a high price, resulting in higher profits.

However, given the arduous or time-consuming nature of developing new oil reserves, a price rise resulting from production challenges will likely lead to reduced quantities sold, which would not affect these companies' earnings or return on equity.

Moreover, the prospective nature of these equity returns should consider that this reasoning applies to simultaneous shocks to supply and demand and anticipated fluctuations in supply and demand. Ready (2018) characterizes demand shocks as the component of returns relative to a global stock index composed of oil-producing companies, that is independent of fluctuations in the innovations volatility index (VIX). In this conceptual framework, the fluctuations in the VIX are treated as a means to regulate comprehensive variations in market discount rates that influence the stock returns of oil-producing enterprises, simultaneously used as a proxy for risk shocks. Supply shocks are represented by the residual component of oil price variations, which is orthogonal to demand and risk shocks.

The decomposition framework proposed by Ready (2018) is represented in the subsequent matrix configuration :

$$X_t = AZ_t \tag{5.1}$$

Where $X_t = [\Delta\text{oil}_t, R_t^{\text{Prod}}, \xi_{\text{VIX},t}]'$ represent a vector with three components, Δoil_t represents the change in oil price, R_t^{Prod} corresponds to the return on the world stock market index of oil-producing companies, and $\xi_{\text{VIX},t}$ is the innovation linked to the VIX, determined by an ARMA(1,1) specification.

Our emphasis is on $Z_t = [s_t, d_t, v_t]'$, constituting a 3×1 vector encompassing oil supply, demand, and risk shocks denoted by s_t , d_t , and v_t respectively. Finally, A takes the form of a 3×3 coefficient matrix, defined as :

$$A = \begin{bmatrix} 1 & 1 & 1 \\ 0 & a_{22} & a_{23} \\ 0 & 0 & a_{33} \end{bmatrix} \quad (5.2)$$

In order to maintain orthogonality between the three distinct categories of shocks, Ready (2018) imposes the following condition :

$$A^{-1}\Sigma_X(A^{-1})^T = \begin{bmatrix} \sigma_s^2 & 0 & 0 \\ 0 & \sigma_d^2 & 0 \\ 0 & 0 & \sigma_v^2 \end{bmatrix} \quad (5.3)$$

where Σ_X signifies the covariance matrix of the variables within X_t , while σ_s^2 , σ_d^2 , and σ_v^2 represent the variances of the supply, demand, and risk shocks, respectively.

The expression presented in equation (3) can be interpreted as a reconfiguration of the usual orthogonalization technique used to establish structural shocks in the SVAR analysis.

In this framework, the volatility of oil price shocks is not normalized to unity. On the contrary, the aggregate sum of these three shocks must intrinsically correspond to the total fluctuation observed in the oil price, as defined by their construction. In the approach used to decompose oil shocks, an oil supply shock is defined as that part of oil price oscillations that is not explained by changes in global aggregate demand and changes in financial market uncertainty.

5.3.2 TVP-SVAR-SV

After decomposing oil shocks into supply, demand, and risk shocks, the following step is formulating the time-varying structural multivariate model. Integrating the structural approach introduced by Ready (2018) with the dynamic Bayesian methodology of Primiceri (2005) and Nakajima (2011), our next step is to build the TVP-SVAR model with stochastic volatility. The objective is to identify the evolutionary propagation of supply, demand, risk shocks, and shocks to carbon market returns, without dividing the data set into subgroups. The selection of the TVP-SVAR-SV model is based on its adaptability, which allows both the transmission mechanism and the volatility of shocks to vary over time while preserving the precise information in the data set.

This observation is more critical when we consider that applying an ad hoc hypothesis, assuming a constant variance for structural shocks, can introduce biases into the estimation results. In particular, previous research by Sims (2001) and Stock (2001) has highlighted the implications of such biases, emphasizing the need for a more nuanced approach to account for potential variations in the variance of structural shocks. From an economic point of view, it is conceptually reasonable to envisage that apparent alterations in variance resulting from structural changes, whether arising from endogenous events such as the global financial crisis or exogenous factors such as the health crisis, should correlate significantly with periods characterized by increased uncertainty. With substantial implications for the fundamental economic framework, these instances of uncertainty are likely to exert significant influences on fundamental aspects such as oil price oscillations, real economic dynamics and, therefore, carbon markets. This dynamic interaction is likely to lead to a series of alterations in time-varying regimes.

The main objective is to detect variations in carbon market returns as a response to identified structural shocks over time while avoiding errors arising from the arbitrary selection of transition dates. Drawing on the research of Primiceri (2005) and Nakajima (2011), we extend this approach by incorporating stochastic volatility into the identification process proposed by Ready (2018).

By referring to Primiceri (2005) and Nakajima et al. (2011), the SVAR model can be expressed as follows :

$$y_t = X_t\beta + A^{-1} \sum v_t \quad (5.4)$$

In this context, X_t is formulated as $I_i \otimes (y_{t-1}, \dots, y_{t-i})$, where \otimes represents the Kronecker product. The vector β has dimensions of $(16i + 4) \times 1$, and the matrix Σ is a diagonal matrix sized 4×4 , featuring a diagonal composed of $[\sigma_1, \sigma_2, \dots, \sigma_4]$.

Integrating the time component in equation (4) leads to the emergence of the following representation for the TVP-SVAR-SV model :

$$y_t = X_t\beta_t + A_t^{-1} \sum_t v_t, \quad t = s + 1, \dots, n \quad (5.5)$$

Equation (5) represents the observation equation of the time-varying structural model integrated with stochastic volatility. Note that all elements, namely β_t , A_t , and Σ_t , exhibit time-varying fluctuations. Following the analytical frameworks proposed by Primiceri (2005) and Nakajima et al. (2011), we conjecture that the parameters governing the conformation of equation (5) imply a stochastic progression, consistent with the nature of a random walk process, thus positing the following proposition :

$$\begin{cases} \beta_{t+1} = \beta_t + u_{\beta t} \\ a_{t+1} = a_t + u_{at} \\ h_{t+1} = h_t + u_{ht} \end{cases} \quad (5.6)$$

As Primiceri (2005) explains, the variance-covariance matrix encompassing innovations in time-varying parameters has a diagonal block configuration, as shown below :

$$\begin{pmatrix} v_t \\ u_{\beta t} \\ u_{at} \\ u_{ht} \end{pmatrix} \sim N \left(0, \begin{pmatrix} I & 0 & 0 & 0 \\ 0 & \Sigma_{\beta} & 0 & 0 \\ 0 & 0 & \Sigma_a & 0 \\ 0 & 0 & 0 & \Sigma_h \end{pmatrix} \right) \quad (5.7)$$

Where Σ_{β} , Σ_a , and Σ_h represent diagonal matrices.

Using the principles of Bayesian inference, TVP-SVAR-SV is estimated by applying the Markov Chain Monte Carlo (MCMC) technique.

The selected prior distribution is very similar to that used by Nakajima (2011). They imply that i th diagonals of the covariance matrices follow distributions $(\Sigma_{\beta})_i^{-2} \sim \text{Gamma}(40, 0.02)$ and $(\Sigma_a)_i^{-2} \sim \text{Gamma}(4, 0.02)$, and $(\Sigma_h)_i^{-2} \sim \text{Gamma}(4, 0.02)$.

Furthermore, in line with the approach established by Primiceri (2005), the Gibbs sampler is used to generate samples derived from posterior distributions. In line with this sampling methodology, the initial 1,000 samples are disregarded as a run-in period in this study, after which 10,000 samples are subsequently drawn.

5.3.3 Data

The dataset used for the empirical analysis comprises monthly data from January 2014 to March 2023. It includes carbon markets data and oil supply, demand and risk shocks, classified by Ready (2018). The definitions of these variables are presented in Table 2.

Table 3 shows the descriptive statistics of the data used. Concerning the three oil shocks, the decomposition of oil price fluctuations shows that oil demand and supply shocks have the highest mean values, with oil demand shocks at 146.27 and oil supply shocks at 62.53. Moreover, their respective standard deviations of 25.96 and 20.60 indicate that these two types of shock not only have the largest amplitudes, but also tend to exhibit greater volatility. We note that the standard deviation of risk shocks remains high (5.33) compared to that of carbon markets, reflecting the high degree of volatility of oil shocks.

TABLE 5.2 – Variable Definition

Variable	Definition	Source
Supply Shock	The residual component of oil price changes.	Investing.com
Demand Shock	The proportion of returns on a worldwide stock index of oil-producing companies.	DataStream
Risk shock	The CBOE Volatility Index (VIX) is a real-time market index representing the market's expectations of volatility over the next 30 days.	Investing.com
EU-carbon	The current market price of European Union Allowances (EUAs) for carbon emissions trading in the spot market, reflecting the cost of emitting one tonne of CO ₂ e in the European carbon market	Thomson reuters database
CH-carbon	The current market price of carbon allowances in the Guangdong emissions trading scheme, representing the cost of emitting one tonne of CO ₂ e in the regional carbon market.	Thomson reuters database

TABLE 5.3 – Descriptive statistics

Variable	Obs	Mean	Std. Dev.	Min	Max	Skewness	Kurtosis
Oil Supply	111	62.5315	20.6043	16.7	114.34	0.6388	2.7709
Oil Demand	111	146.2707	25.9622	83.1	215.7	0.2751	2.9793
Oil Risk	111	0.0126	5.3290	-10.1416	23.1938	1.8522	7.9252
EU-carbon-returns	111	0.0246	0.1260	-0.4393	0.3293	-0.6596	4.5587
CH-carbon-returns	111	0.0031	0.1064	-0.3606	0.3784	-0.3343	5.5921

Figure 1 illustrates the evolution of oil supply, demand, and risk over the study horizon. The oil supply and demand series experienced periods of erratic fluctuation and decline during the oil crash of 2014-2016, phase 1 of the COVID-19 pandemic, and the Russian-Ukrainian war of 2022. Similarly, the risk shock series showed high levels of fluctuation and volatility during these same events. Similarly, Figure 2 shows the time-series evolution of carbon market returns in Europe and China. We observe that in Europe, the level of volatility is high during three major events : the oil crash, the COVID-19 pandemic, and the Russian-Ukrainian war. However, Chinese carbon market returns showed high volatility during the oil crash and the US-China conflict on 2016, with relatively lower volatility during the Russian-Ukrainian war than the European market.

We use the unit root test with structural breaks proposed by Kapetanios (2005) to assess the integration characteristics of the variables. This method is particularly appropriate when considering structural changes that impact the stationarity of the variables used. The results of unit root tests with structural breaks are presented in Table 3. The results clearly show that the variables CarbonEU, CarbonCH, Oil Supply, and Oil Demand exhibit stationarity when analyzed in their first differences, while Oil risk is stationary in level.

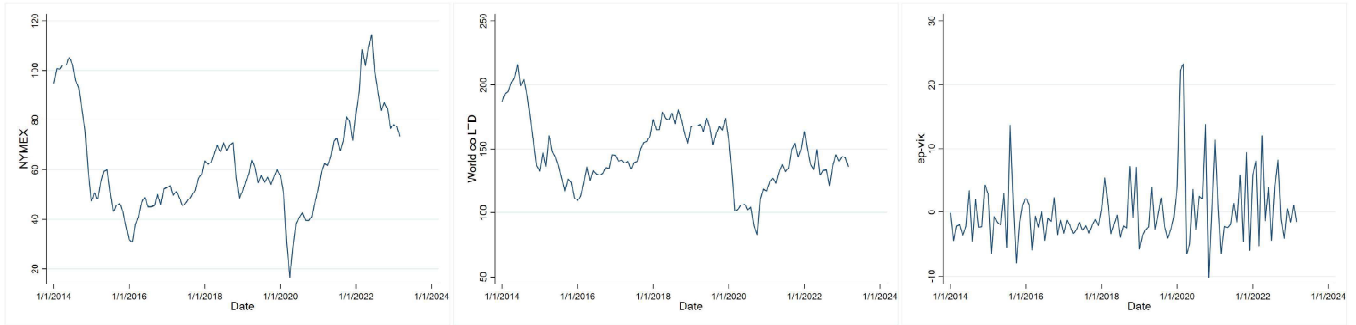


FIGURE 5.1 – Oil shocks from January 2014 to March 2023

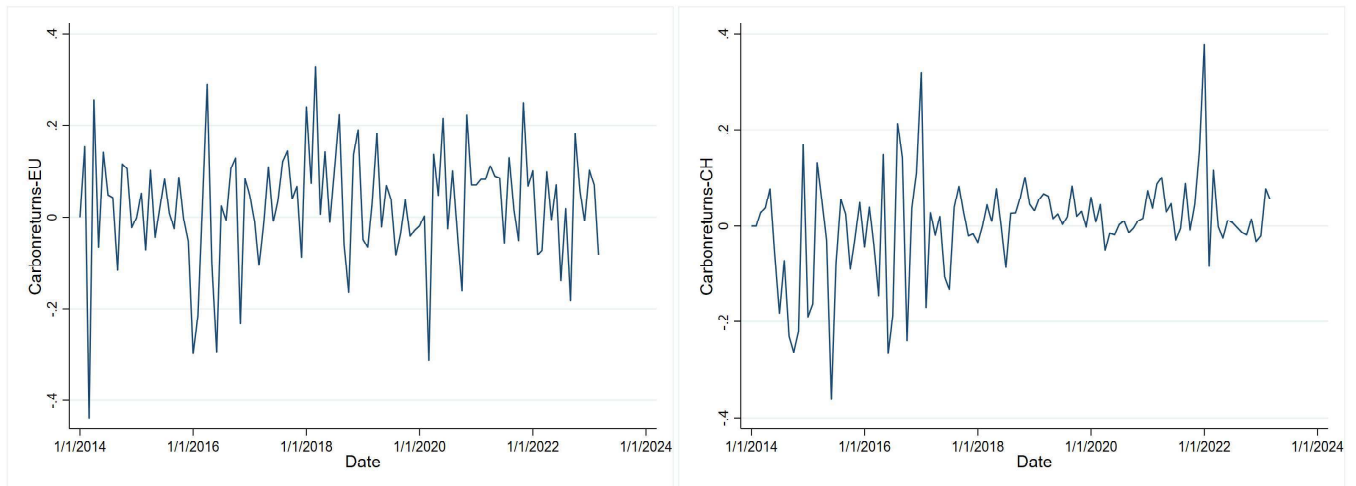


FIGURE 5.2 – European and Chinese carbon returns from January 2014 to March 2023

TABLE 5.4 – Kapetanios (2005) unit root tests with structural breaks

	Level			1st Diff		
	K=1	K=2	K=3	K=1	K=2	K=3
CarbonEU	-4,04397 2021 :01 :00	-5,18127 2021 :01 :00 2018 :02 :00	-5,23552 2021 :01 :00 2018 :02 :00 2015 :12 :00	-12,6701*** 2020 :10 :00	-12,808*** 2020 :10 :00 2017 :07 :00	-12,808*** 2020 :10 :00 2017 :07 :00 2016 :01 :00
CarbonCH	-2,34109 2021 :08 :00	-5,07331 2021 :08 :00 2016 :05 :00	-5,30228 2021 :08 :00 2016 :05 :00 2018 :09 :00	-6,02433*** 2015 :07 :00	-6,18678*** 2015 :07 :00 2021 :08 :00	-6,19993 2015 :07 :00 2021 :08 :00 2018 :07 :00
Oil Supply	-3,33966 2019 :12 :00	-6,05106* 2019 :12 :00 2016 :01 :00	-6,36101 2019 :12 :00 2016 :01 :00 2021 :08 :00	-10,2931*** 2016 :01 :00	-10,704*** 2016 :01 :00 2020 :10 :00	-10,704*** 2016 :01 :00 2020 :10 :00 2017 :08 :00
Oil Demand	-4,14894 2020 :04 :00	-4,14894 2020 :04 :00 2018 :05 :00	-4,14894 2020 :04 :00 2018 :05 :00 2016 :10 :00	-8,90546*** 2020 :04 :00	-9,61488*** 2020 :04 :00 2016 :02 :00	-9,61488*** 2020 :04 :00 2016 :02 :00 2017 :08 :00
Oil Risk	-11,0406*** 2019 :12 :00	-11,0406*** 2019 :12 :00 2021 :08 :00	-11,0406*** 2019 :12 :00 2021 :08 :00 2016 :02 :00	-9,36756*** 2020 :03 :00	-9,68489*** 2020 :03 :00 2015 :09 :00	-9,80709*** 2020 :03 :00 2015 :09 :00 2018 :03 :00

Note : The Kapetanios (2005) test assumes, under the null hypothesis, the presence of a unit root with no structural breaks. Conversely, the alternative hypothesis assumes stationarity with structural breaks. Initial-level series are tested using models with ordinate and trend specifications, while first-difference series are tested using only models with ordinate specifications. We use ***, **, and * in the results to signify statistical significance at the 1%, 5%, and 10% significance levels, respectively.

5.4 Results and discussion

5.4.1 Estimation of selected parameters

In this study, the estimation of our TVP-SVAR-SV model was established with a lag length set to 1, according to Akaike's information criterion (AIC) and the Hannan-Quinn information criterion (HQ). Table 5 provides a summary of the estimated results for the selected parameters, which includes posterior means, standard deviations, 95% confidence intervals, and diagnostic statistics for Geweke convergence and inefficiency. Firstly, these results confirm that the mean a posteriori parameter estimates remain within their respective 95% confidence intervals. Secondly, our results indicate that at a 5% significance level, the null hypothesis of convergence to the posterior distribution is not rejected for any of the parameters, as suggested by the Geweke statistics. Finally, it should be noted that almost all parameters exhibit remarkably low inefficiency factors, implying that posterior draws are efficiently generated by the Markov chain Monte Carlo (MCMC) algorithm. Figure 3 represents the sample autocorrelations, sample paths, and posterior densities. The results presented in these Figures show that the sample's autocorrelation coefficient decreases rapidly and exhibits minor fluctuations, signifying the absence of autocorrelation in the sample data. The sample trajectory remains consistent, suggesting the stability of the data extracted from the sample. In addition,

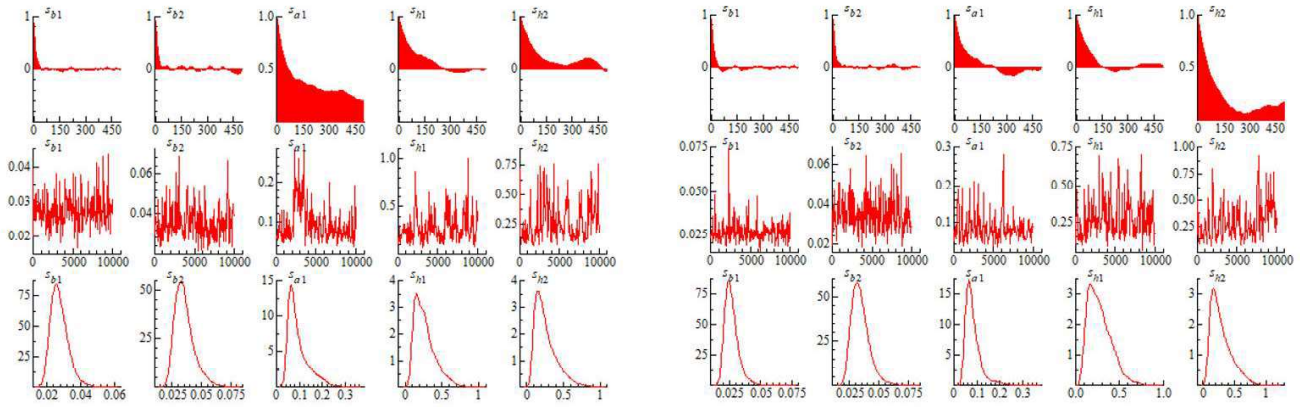


FIGURE 5.3 – Distribution plot of MCMC-based parameter estimates for Europe and China

the posterior density maps all show normal distributions, indicating that the extracted sample is sufficient. These observations collectively demonstrate the validity and independence of the MCMC sampling results, affirming a robust model fit.

TABLE 5.5 – TVP-SVAR model parameter estimation results

Parameter	Mean	Stdev	95%L	95%U	Geweke	Inef.
Europe						
$(\Sigma\beta)_1$	0.0270	0.0060	0.0189	0.0416	0.273	18.95
$(\Sigma\beta)_2$	0.0342	0.0078	0.0227	0.0530	0.830	24.92
$(\Sigma a)_1$	0.0840	0.0363	0.0425	0.1893	0.291	94.47
$(\Sigma h)_1$	0.2800	0.1332	0.0969	0.5978	0.000	99.60
$(\Sigma h)_2$	0.2899	0.1684	0.0804	0.7021	0.006	143.49
China						
$(\Sigma\beta)_1$	0.0277	0.0053	0.0196	0.0401	0.038	17.42
$(\Sigma\beta)_2$	0.0355	0.0084	0.0232	0.0562	0.070	27.92
$(\Sigma a)_1$	0.0955	0.0468	0.0438	0.2147	0.015	178.61
$(\Sigma h)_1$	0.2711	0.1446	0.0890	0.6291	0.112	131.69
$(\Sigma h)_2$	0.2621	0.1534	0.0788	0.6488	0.053	133.63

5.4.2 Stochastic volatility estimation

Beginning with the temporal evolution of estimated stochastic volatilities arising from the variables, denoted as $\sigma_{i,t}^2 = \exp(h_{i,t})$, represented in Figure 4, we utilize the posterior mean and 95% credibility intervals. This visualization effectively highlights the substantial fluctuations in volatility over different periods, underlining the need to use the SVAR TVP model with stochastic volatility. This selection prevents potential biases in the estimates, an essential consideration given the importance of a posteriori estimates of stochastic volatilities.

Stochastic volatilities show significant variations over time, with distinct profiles. Regarding the oil supply (OS)

and the oil demand (OD) graphs, a substantial and sharp increase in stochastic volatility is evident between 2014 and 2015. This increased volatility can be attributed to the collapse in oil prices in 2014. The graphs also show that oil supply volatility rapidly declined (and returned to normal) from 2017 onwards. Conversely, the graph of stochastic oil demand volatility reveals a rapid decline in volatility, followed by a gradual increase, from around 2018. Notably, oil demand volatility remains considerably higher than oil supply volatility over this period. This upward trend can be attributed to the global move towards energy transition. After 2018, the focus shifted to renewable energies and sustainable development. This shift towards cleaner energy sources, coupled with changes in government policies such as carbon pricing and emissions regulations, could influence oil demand trends. The resulting uncertainty over energy policy and the pace of the energy transition may contribute to the observed volatility in oil demand. In addition, a remarkable level of stochastic volatility was observed after 2022, which may be associated with the Russian and Ukrainian wars.

The financial risk related to the decomposition of the oil price by Ready (2018) highlights distinct periods of high volatility. These periods correspond to major events and crises, including the 2014 oil crash, the COVID-19 pandemic in 2020 and 2021, and the Russian-Ukrainian war in 2023. These events highlight the sensitivity of financial markets to geopolitical, economic, and public health crises, making risk assessment and management crucial for investors and stakeholders in the energy sector.

The graph describing stochastic volatility in the Chinese carbon market, focusing on the Guangdong carbon market, highlights the relatively lower levels of volatility compared to Europe. The notable spike in volatility during 2016/2017 can be directly linked to China's efforts to align with the Paris Agreement and implement new carbon-related policies. This demonstrates the significant influence of government policies and international commitments on market dynamics and highlights the need for careful analysis and risk management in carbon markets. The stochastic volatility peaks observed in the European carbon market in 2014 and 2016 are linked to the oil crash and Brexit, respectively. In addition, the higher overall volatility in the European market compared to China can be attributed to market maturity, regulatory complexity, and policy sensitivity in European carbon trading.

5.4.3 Time varying impacts of decomposed oil price on carbon markets

To explore the dynamic effects of oil demand, supply, and risk shocks on carbon market returns, we use the time-varying impulse response functions for further analysis. The results of time-varying responses are presented in Figure 5 for Europe and China. The response curves, observed with lags of 1 period (representing one month), 3 periods (equivalent to one quarter), and 6 periods (corresponding to half a year), illustrate short, medium, and long-term market reactions, respectively. The impact of oil supply, demand, and financial risk shocks on carbon market returns changes over time, both in Europe and China. Generally, as shown in Figure 5, short- and medium-term responses to oil supply, demand, and financial risk shocks on carbon markets are more important than long-term

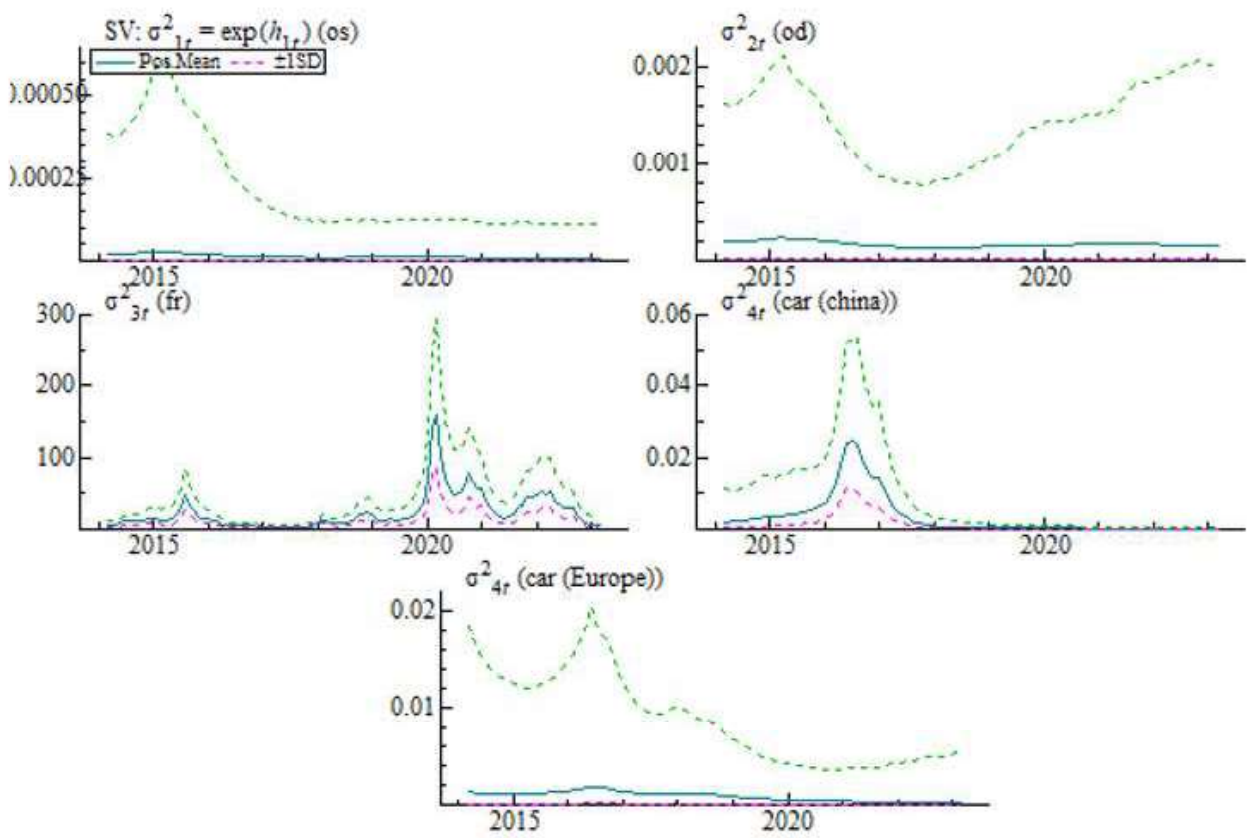


FIGURE 5.4 – Posterior estimates of stochastic volatilities of structural shocks

responses in all cases. Looking closely at Figure 5, it is clear that the European carbon market generally reacts positively to oil supply and demand shocks when observed at 1 and 3 lag periods. However, distinct variations appear when the analysis is extended to a 6 lag period. In particular, in the long term, the reactions of carbon yields to oil supply and demand shocks tend to be mainly negative over the whole period.

In addition, we have found that a positive shock to oil supply and demand almost has a positive impact on European carbon market returns, meaning that there is a significant increase in carbon market returns during major events. Furthermore, as Figure 5 shows, financial risk shocks mainly exert alternating positive and negative impacts on carbon market returns. These effects generally decrease after around six months and can be attributed to a series of key major events. In particular, the shocks observed regarding oil demand, supply, and financial risk correspond to several major events, including Brexit in 2016, the European debt crisis in 2018, the start of the COVID-19 pandemic, and the Russian-Ukrainian war at the beginning of 2022. Thus, our results indicate that oil supply and demand shocks have positive effects on European carbon market returns in the short and medium term. At the same time, they tend to have a negative and comparatively minor impact in the long term. Conversely, financial risk shocks linked to oil prices generally negatively impact European carbon market returns, which increase in major events. These events are closely associated with a period marked by higher financial risks, as underscored by Bocola et al. (2019).

Regarding supply and demand shocks, the specific impact on carbon market returns would depend on a number of factors, including the scale and duration of the increase in oil prices, Brexit-related political responses, and broader economic conditions. Nevertheless, the interconnectedness of the energy and carbon markets highlights the risk of negative consequences for carbon market returns in the event of a significant rise in energy costs. Furthermore, the influence of the shocks observed in July 2018 coincided with the start of Sino-American trade tensions, which had a significant impact on commodity futures prices, including oil, as shown in the study of Li et al. (2020). High financial risk events, characterized by higher degrees of uncertainty in the financial markets, particularly from the crude oil market, can result in greater risk spillover to the carbon market than lower degrees of uncertainty in the financial markets (Yang and Yang, 2020). As shown in Figure 5, which illustrates the impact of financial risk on European carbon market returns during major events. Such events have the potential to exert negative effects on carbon market returns. These effects materialize through their influence on investor behavior, corporate financial stability, prevailing economic conditions, political responses, market dynamics, and general market sentiment.

Moving on to the graphic of time-varying impulse responses showing the effects of supply, demand, and risk shocks on the Chinese carbon market, as illustrated in Figure 6, it is clear that these shocks exert a significant effect on Chinese carbon market returns in the short to medium term, while in the long term, these shocks appear to have no significant impact on the Chinese carbon market. Primarily, the analysis of oil supply and demand shocks in Figure 6 reveals a positive impact on Chinese carbon market returns. Notably, the impact of these shocks decreased during the oil crash 2014 and the Russian-Ukrainian war, while it increased in 2016 and 2017 following China's

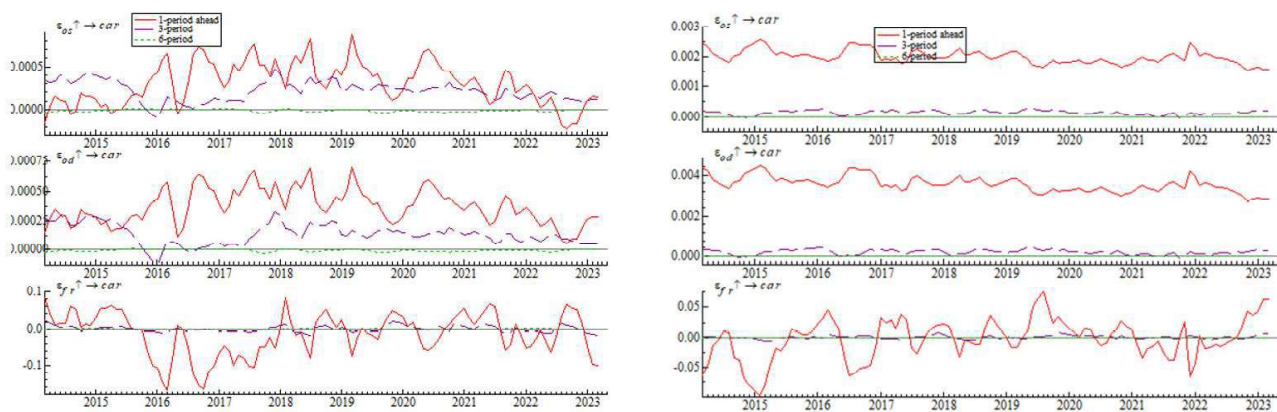


FIGURE 5.5 – Time varying impacts of decomposed oil price on European carbon market

commitment to the Paris Agreement.

The time-varying impact of financial risk on the Chinese carbon market, as shown in Figure 6, clearly shows that periods characterized by high financial risk, such as the oil price crash in 2014-2015, the Sino-US trade friction incident in 2018, the COVID-19 pandemic and the Russian-Ukrainian war in 2022, have a significant and persistent negative influence on carbon market returns. These events correspond with pronounced declines in the Chinese carbon market returns, indicating its heightened sensitivity to financial risk during these major events.

However, it is crucial to emphasize that these impacts, while significant, are comparatively less pronounced on the Chinese carbon market compared to the European ones. While both the European and Chinese carbon markets are influenced by shocks to oil supply and demand, differences in market maturity, political structures, industrial composition, and global context can lead to variations in the scale of their responses. With its extended history and ambitious targets, the European market may be more sensitive to external shocks, as shown in Figure 5.

The carbon market, whether in China or Europe, remains sensitive to financial risk during major global or regional events. Both markets can experience significant fluctuations in response to external shocks, highlighting their shared susceptibility to financial risk in a dynamic and interconnected global landscape. As highlighted by Li et al. (2020) China's financial market experiences abnormal fluctuations influenced by a various factors. These factors encompass the structure of the stock market network, fluctuations in international commodity prices, the performance of international stock indexes, and domestic macroeconomic indicators. In addition, Carbon markets are characterized by a higher degree of volatility than traditional stock markets. This heightened volatility is attributed to the multifaceted nature of carbon prices, which are influenced by a range of factors, including energy price fluctuations, economic policy uncertainties, extreme weather events, and the interaction of supply and demand shocks (Wu and Jiang, 2023).

5.4.4 Time varying impacts of oil supply, demand, and risk shocks on carbon returns at different time points.

We conduct a detailed analysis over different time points to examine the time-varying impact of oil supply, demand, and financial risk shocks on carbon market returns during distinct periods marked by major events. Our focus centers on key years, notably 2014, 2020, and 2022, coinciding with major global events instigating structural shifts in these dynamics : the oil crash in 2014, the COVID-19 crisis in 2020, and the Russian-Ukrainian war in 2022. This selection of global events enables us to make meaningful comparisons between the effects observed in Europe and China rather than focusing on specific events within these regions.

As shown in Figure 5, it is noteworthy that the impact of these oil supply, demand, and risk shocks on the carbon market is significant only in the short term, while it becomes negligible in the medium and long term. This outcome corroborates our earlier findings.

Regarding the reaction of European carbon market returns to different oil shocks, there were notable similarities in the responses of carbon market to oil supply and demand shocks during three major events : the oil crisis, the COVID-19 pandemic, and the Russian-Ukrainian conflict. This observation confirms that, in general, the carbon market tends to react similarly to energy crises, health crises, and geopolitical shocks. In other words, during the crisis, an increase in oil supply and demand will increase the returns of the European carbon market.

Analysis of the impact of financial risk shocks in the oil context on the carbon market reveals a distinct pattern. Figure 5 shows that these financial risk shocks had a negative impact on carbon market returns during the COVID-19 crisis and the Russian-Ukrainian war. Notably, the COVID-19 crisis had the greatest negative impact on carbon market returns. This indicates that during the COVID-19 crisis, increased financial risk significantly reduced carbon returns on the European carbon market. This result can be attributed to various pandemic-related factors, including economic uncertainty, reduced industrial activity, and increased financial instability, which all influenced the carbon market in unique ways during this crisis period.

In the case of the Russian-Ukrainian war, we observe a similar trend, where increased financial risk moderated carbon returns. In the context of the Russian-Ukrainian conflict, the impulse responses of European carbon market returns have consistently shown a negative trajectory.

Geopolitical conflicts, such as that between Russia and Ukraine, can impact regional instability. Several factors contribute to the potential impact of the Russia-Ukraine conflict on the European region. Ukraine's geographical proximity to Europe and its vital role as a transit route for energy resources, particularly natural gas, make it a critical geopolitical point. Any regional disruption, particularly energy supply and transport, can spill over into Europe, affecting energy markets, economic stability, and investor confidence.

As shown in Figure 5, we can also observe an interesting trend during the 2014 oil crisis. Notably, financial risk significantly and positively impacted European carbon market returns during this period. The 2014 oil crisis,

characterized by a significant drop in oil prices, increased energy consumption and production across all sectors, resulting in higher greenhouse gas emissions and demand for carbon emission allowances. This demand, in turn, led to higher carbon market prices, which had a positive impact on European carbon market returns. Investors and market players capitalized on the profit potential of this scenario.

These findings align with the research of Zheng et al. (2021) who showed that Oil supply and demand shocks significantly positively affect EUA returns. Meanwhile, oil risk shocks have a significant negative effect on EUA returns. Figure 5 shows a similar trend, in which the impact of oil supply and demand shocks is systematically positive, reflecting the trend observed in Europe. However, the influence of demand and risk shocks on carbon market returns is significantly different between China and Europe. China, in particular, stands out for the amplified impact of oil demand shocks. This distinction can be attributed to China's greater dependence on oil and the robustness of its industrial sector, which makes it more sensitive to fluctuations in oil demand.

In Figure 5, we observe distinct impulsive responses to financial risk at different points in time. In the 2014 crash oil period, the negative impact of oil companies' increased financial risk on carbon prices in China can be attributed to several factors. Firstly, the Chinese carbon market was relatively new at the time and lacked the robust regulatory framework in more established markets. This relative newness made it more vulnerable to external financial shocks. In addition, the interconnected nature of financial markets meant that turbulence in the oil sector could spill over into other sectors, contributing to the negative impact observed.

Regarding the COVID-19 crisis, We observe an interesting dynamic in which the financial risk associated with oil companies had a notable but relatively minor positive impact on the Chinese carbon market. This effect can be explained by China's efforts to stabilize its economy during the pandemic. Government intervention and stimulus measures mitigated the negative impact of financial risk, resulting in a weaker positive correlation. Finally, during the period of the Russian-Ukrainian war, we observe that shocks related to oil risk had a significant and negative impact on Chinese carbon market returns. This result can be attributed to the increased geopolitical tensions and uncertainties associated with the war, which negatively influenced investor sentiment and, subsequently, carbon market performance.

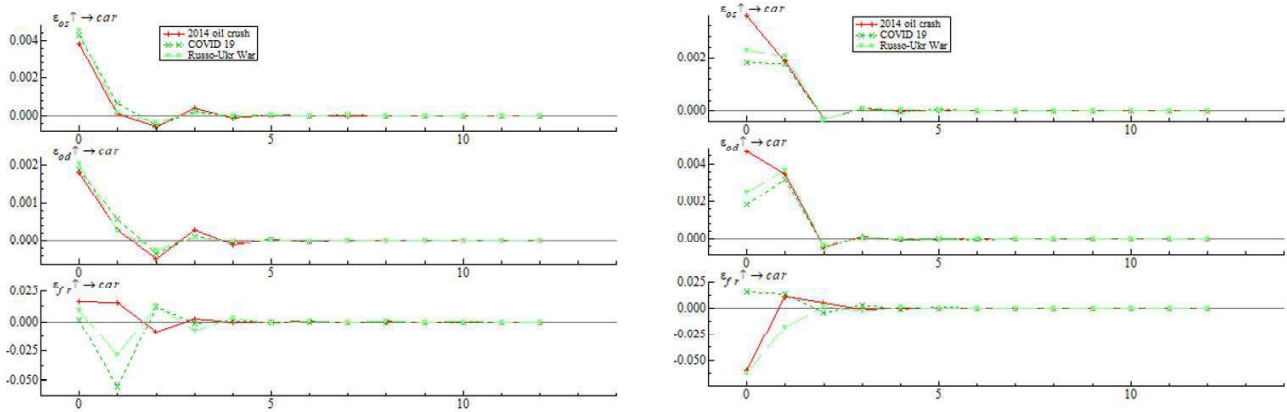


FIGURE 5.6 – Impulse responses of oil supply, demand, and risk shocks to carbon returns at different time points

5.5 Conclusion

A growing number of research studies are focusing on the carbon trading market and how it is influenced by energy markets. However, the impact of oil prices decomposed into different oil shocks of varying origins on carbon allowance returns has been little studied. Furthermore, although the link between the oil market and emissions trading markets has received attention under various market conditions, there is limited research on how different sources of oil shocks affect the carbon market under these various conditions. To fill these gaps, our study examined the effects of oil shocks from different sources on carbon market returns in distinct market contexts.

In this study, we examined how the European and Chinese carbon markets reacted over time to different types of oil shocks, including demand, supply, and risk shocks. Our study covers the period from January 2014 to March 2023. We used the TVP-VAR-SV model, combined with the impulse response function and the time-dependent impulse response function to analyze the time-varying effects of different oil shocks on carbon market returns. Three important global events were also taken into account throughout our analysis : the 2014 oil crash, the outbreak of COVID-19, and the Russian-Ukrainian war.

Overall, our results show a strong correlation between decomposed oil shocks and carbon market returns. At the same time, our findings reveal distinct responses of carbon markets in Europe and China to oil supply and demand shocks and risk-related shocks. Europe consistently shows a positive response to oil supply and demand shocks, accompanied by a negative response to risk shocks, underlining market stability and investment potential. In contrast, China’s carbon market shows a much stronger positive response to oil demand shocks, reflecting its dependence on oil and the strength of its industrial sector. However, it proved more sensitive to oil-related financial shocks, particularly during the 2014 oil crisis, due to its carbon market’s relative newness and limited regulatory framework. Given the unique characteristics of each region’s carbon market, these findings underline the importance of appropriate policies and strategies for investors, policymakers, and regulators.

Our findings have important implications for regulators, policymakers, and market investors in Europe and China. Firstly, in Europe, where the carbon market exhibits a consistently positive response to oil supply and demand shocks, policymakers should focus on maintaining a stable regulatory framework to boost investor confidence. This includes strengthening mechanisms to deal with short-term shocks, while encouraging the diversification of energy sources to reduce sensitivity to external fluctuations in the oil market. Collaborative efforts to harmonize regional carbon market policies can further promote global stability and emissions reductions. Moreover, European investors should recognize the potential for positive returns in response to oil shocks, and consider sustainable investments in this context.

In China, where the carbon market has unique characteristics, policymakers should prioritize strengthening regulatory oversight, particularly given the market's relative immaturity and vulnerability to external financial shocks. Policies should focus on monitoring and mitigating financial risks in sectors impacting the carbon market, particularly the oil industry. In addition, policymakers should assess the influence of different market conditions, as our results suggest greater sensitivity during a market crisis. For investors in China, it is essential to identify the sources of oil shocks and adapt to fluctuations in carbon returns while being more risk-averse, especially when markets are declining. These adapted strategies and policies, which consider the distinct characteristics of each region's carbon market, will contribute to market stability and support global efforts to combat climate change.

Chapitre 6

The interconnectedness of carbon, fossil fuels, and clean energy markets in the context of climate change

Abstract ¹

Carbon allowances represent a crucial financial instrument for mitigating the consequences of global warming and climate change. However, the feedback mechanism for Carbon-Energy-Finance systems introduces complexity due to the incorporation of equity, bond, and non-energy commodity assets. This study examines the volatility dynamics between carbon markets in Europe and China and their interactions with fossil fuel and renewable energy markets. To measure this connectivity, we use advanced methodologies, such as the Diebold and Yilmaz method, to shed light on the complex relationships between these two markets. Our study reveals distinct results between China and Europe : the Chinese carbon market has stronger connectivity in terms of return spillovers, which capture price variations, with other markets, while the European carbon market has stronger connectivity in terms of volatility spillovers, which capture uncertainty, with various renewable energy sources. In the specific contexts of China and Europe, these results provide valuable insights for policymakers and investors interested in tailoring approaches to sustainable energy transitions and financial stability.

1. This chapter is an article written solely by me

6.1 Introduction

Climate change has become one of the most serious challenges to sustainable development (Alharthi et al., 2022). The origins of this environmental crisis lie primarily in greenhouse gas (GHG) emissions, mainly generated by fossil fuel combustion (Gong et al., 2021). Recent data from the International Energy Agency (IEA) underline the gravity of the situation, revealing that carbon dioxide emissions from the fossil fuel energy sector have reached an all-time peak in 2022 (see Figure 1). This rising trend in carbon emissions has propelled the problem to the forefront of urgent global concerns, all the more so as industrialization advances rapidly (Su et al., 2022).

In response to this crucial problem, the carbon market (CETS), an important institutional innovation introduced under the Kyoto Protocol, has gained importance (Liu and Zhang, 2021). It deals with carbon emission allowances as tradable commodities and uses market mechanisms to reduce emissions and profitably encourage low-carbon development (Fang et al., 2018). Although mainly driven by political considerations, the CET market has financial characteristics close to traditional energy markets (Wu and Liu, 2022).

In addition, the price dynamics of conventional fossil fuels, driven by the principles of supply and demand, are intimately linked to CO₂ emissions, exerting a significant influence on the carbon market (Gong et al., 2021). This interaction underlines the potential of carbon pricing as a powerful instrument for encouraging the transition to renewable energy sources (Zhang et al., 2022). As a result, initiatives to make coal and other fossil fuel production more expensive have attracted attention, prompting investors to turn to clean energy markets rather than traditional ones (Ding et al., 2022).

It is essential to recognize that the expansion of the ETC market should not be considered in isolation from developments in the fossil fuel and renewable energy sectors due to the complex price interdependencies between these markets (Ding et al., 2023). The European Union Emissions Trading Scheme (EU ETS) began in 2005 and is currently the world's largest carbon market (Ye et al., 2021). Operating on a cap-and-trade basis, this initiative involves regulatory control of the total permitted volume of CO₂ emissions over specific periods, with tradable credits distributed accordingly (Adekoya et al., 2021; Liu and Zhang, 2021). It is important to note that there is a gradual shift from the free allocation of carbon allowances to adopting auctions for distribution under this system (Dai et al., 2021).

As a central element of EU climate policy, the EU ETS, part of a broader set of carbon markets, plays a pivotal role in the EU's commitment to achieve net zero emissions by 2050 (Ye et al., 2021). However, while the financialization of this market has improved trading liquidity and facilitated transactions, it has also introduced price volatility and speculative trading elements. The EU ETS has seen notable price fluctuations due to financial instability and uncertainties surrounding energy policies, such as the proposed increase in the emissions reduction target for 2030 from a 40% reduction to at least 55%, as suggested by the European Commission. Moreover, Carfora et al., (2022) prove that various factors have all contributed to higher energy prices and made the dynamics of carbon pricing

more complex. These factors include the economic recovery following COVID-19, the shift away from fossil fuels to renewables in the energy sector, and geopolitical tensions linked to the conflict between Russia and Ukraine.

Similarly, China's rapid economic growth has led to a considerable increase in energy consumption, particularly from non-renewable sources. In fact, by 2020, China claimed the title of the world's largest energy consumer (Zhang et al., 2017). Its high dependence on fossil fuels has resulted in significant carbon dioxide emissions. The Chinese government has been actively engaged in climate change initiatives in response to the global call for climate action under the Sustainable Development Goals. Although still maturing, China's green finance and carbon trading markets still need to be developed to be similar to the European market. Nevertheless, as the world's second-largest economy, China can boast Chinese financial institutions have consistently ranked first in the world for green loan balances in domestic and foreign currencies. By December 2021, cumulative allowance sales on China's various pilot carbon trading markets had almost reached 400 million tonnes, with total sales exceeding 9 billion yuan². In recent years, the Chinese government has implemented a series of measures to optimize energy consumption, meet carbon emission reduction targets, and promote the growth of renewable energy and green finance. These initiatives include the introduction of pilot carbon emissions trading (CET) programs in various regions and the promotion of sustainable energy sources (Zhao et al., 2016).

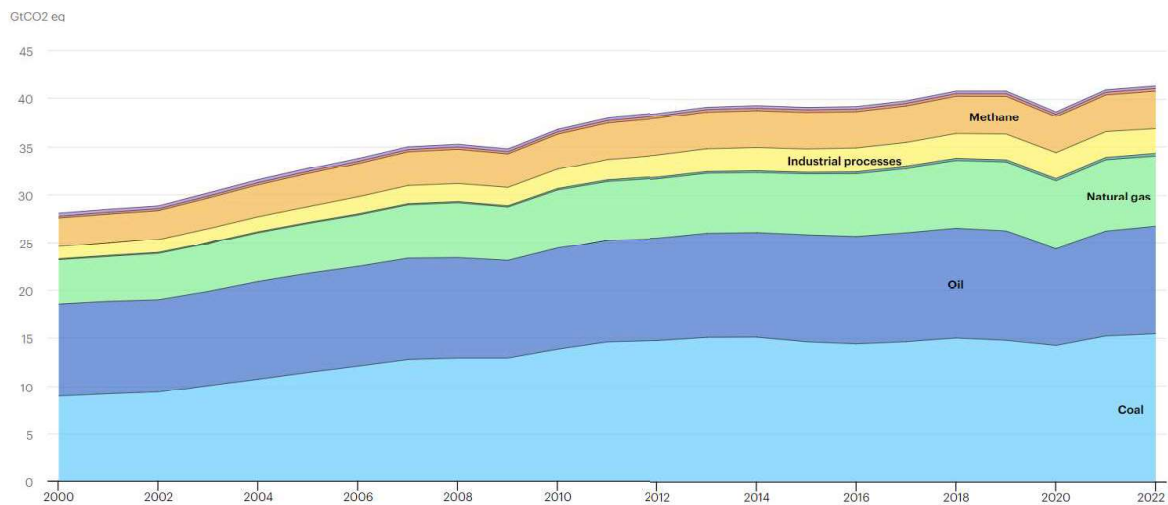
Faced with growing concerns in Europe about the energy crisis and the urgent issue of climate change, member states are faced with the imperative challenge of striking a delicate balance between ensuring energy security, maintaining price stability, and meeting their commitments to net-zero targets.

This complex landscape is further complicated by the evolving interconnections between carbon, conventional, and renewable energy markets (Ding et al., 2022). In addition, the forces of financial liberalization and technological advances highlight the increasingly complex interplay of dependencies and greater integration between different sectors in both Europe and China. In light of these multi-dimensional perspectives, this study explores the dynamic interconnectedness between the European /Chinese ETS and conventional and clean energy markets indices.

The primary objective is to provide policymakers with information to help them formulate a well-informed carbon trading strategy that facilitates the transformation of energy consumption patterns and improves the possibility of achieving ambitious emission reduction targets. Furthermore, by exploring the potential integration of carbon markets into well-structured portfolios as plausible hedging and diversification mechanisms (Ji et al., 2018), this research is looking to provide valuable recommendations for investors and other market stakeholders considering risk diversification and portfolio management strategies.

The second key contribution of this study is the comparative analysis of the European and Chinese carbon markets and their interaction with fossil fuels and clean energy indices. This comparison offers valuable insights into how different policies, market structures, and economic conditions shape the relationship between carbon markets and energy sectors in different geopolitical and economic contexts. By comparing these experiences, we can better

2. Source : http://www.gov.cn/xinwen/2020-10/28/content_5555655.htm, accessed on September 2023



IEA. Licence: CC BY 4.0

FIGURE 6.1 – Global energy-related greenhouse gas emissions, 2000-2022
Source : IEA

understand the complexities of carbon trading and their impact on energy transitions in both regions.

This study is divided into five sections. Following this introduction, section 2 reviews the literature, section 3 deals with issues relating to the data and methodology employed, section 4 presents and discusses the results, and section 5 concludes the study.

6.2 Literature review

This section provides an overview of the previous research. We look at the complex links between carbon markets, fossil fuels, and clean energies. The relationship between these markets is of significant importance in environmental economics and energy management, particularly in tackling climate change and achieving sustainability goals. The literature review presents in Table 1 a set of studies highlighting variations in interconnections between markets in various regions. It emphasizes examining the interconnection and how shocks are transmitted within these markets using various methodologies. In addition, it highlights the significant differences observed in the findings of these studies, highlighting the need for further research to provide more in-depth and clearly defined insights into the complex relationship between carbon markets, fossil fuels, and clean energy indices in two distinct market conditions.

TABLE 6.1 – Literature Review Summary Table

Authors	Region/country	Study Period	Methodology	Major findings
Ji et al. (2018)	Europe	From July 17, 2006, to October 31, 2017.	VAR model	Brent oil prices exert a significant influence on carbon price fluctuations and associated risks and the volatility system displays higher interconnectedness compared to the returns system.
Wang and Guo (2018)	Europe	From January 10, 2006, to May 31, 2017.	Diebold and Yilmaz (2012)	WTI oil market transmits the strongest spillover effect to the Brent oil, natural gas and carbon market. In addition, the spillover effect of natural gas to carbon market is also prominent
Chen et al. (2019)	Europe	From July 2, 2007 to June 13, 2016.	Asymmetric BEKK model	The correlation between European carbon market and Brent oil and natural gas is positive and significant.
Tan et al. (2020)	Europe	From March 4, 2008, to July 17, 2018.	Modified error variance decomposition and network diagrams	The European carbon market tends to be more strongly linked to energy assets as compared to financial assets, as its strongest links to non-energy commodity markets and stock markets are less significant than those of oil and midstream.
Naeem et al. (2020)	Europe	From August 2014 to December 2016.	Diebold and Yilmaz (2012) and Baruník and Křehlík (2018)	Increased market connectivity during global financial crises and the shale oil revolution, impacting oil, carbon, electricity, and clean energy markets.
Duan et al. (2021)	Europe	From January 07, 2013 to March 30, 2019.	Quantile on Quantile (QQ) and the causality-in-quantiles methods	When the economy is strong and the carbon price is high, the impact of energy prices on the carbon price is less significant than when the economy is weak and the carbon price is low.
Hanif et al. (2021)	Europe	From May 18, 2011, to March 05, 2020.	Time-scale spillover index	Positive and dynamic relationship between carbon prices and clean and solar indices, and asymmetrical relationship between carbon prices and renewable energy, technology, and wind indices.
Gong et al. (2021)	Europe	From January 1, 2009 to December 31, 2018.	TVP-VAR-SV model	The study finds time-varying and asymmetrical spillover effects between the carbon and fossil energy markets, with coal having the strongest impact on the carbon market.
Ding et al. (2022)	Europe	From March 26, 2010 to June 10, 2021.	Diebold and Yilmaz (2012) and Baruník and Křehlík (2018)	The carbon market is a net receiver of spillovers from the oil and clean energy markets in the short run but becomes a net emitter of spillovers to the coal and gas markets in the long run.
Wu et al (2022)	China	From April 23, 2014 to December 31, 2020.	Diebold-Yilmaz and Baruník-Křehlík methods	China's regional carbon emission trading markets show primarily short-term and negative net spillovers. The spillovers from the natural gas market to carbon emission trading markets have surpassed those from the coal market since 2018.
Zhu et al. (2023)	Europe and China	From July 16, 2021 to April 25, 2023.	NAGARCHSK-Mixed Copula	In the context of crude oil, the Chinese carbon market is slightly less favorable than the European carbon market in terms of hedging costs and stability, but has superior hedging efficiency.
Dogan et al. (2023)	Global	From August 01, 2014 to February 04, 2022.	TVP-VAR model	Among alternative renewable sources, solar power and biofuels are the biggest net shock emitters, with wind and solar power being the main sources of global carbon shocks.
Jiang et al (2023)	China	From March 27, 2018, to January 5, 2023	Diebold and Yilmaz (2012) and Baruník and Křehlík (2018)	The carbon price fluctuations are mainly influenced by non-renewable energy. Non-renewable energy and carbon markets are the main net recipients and can be used as hedge assets
Qiao et al (2023)	China, the US and Europe	From December 2009 to June 2022.	Network topology analysis and Diebold and Yilmaz (2012)	The total spillover index shows, that spillover between the energy and carbon markets varies over time, particularly during extreme events.

6.3 Data and Methodology

6.3.1 Data

This study focuses on a monthly dataset covering the period from January 2014 to April 2023. The selection of the 2014-2023 period is also influenced by the availability of complete and reliable data during these years in both contexts. Moreover, the period includes major events such as the COVID-19 pandemic, the renewable energy investment boom, and the ongoing conflict in the Russian-Ukrainian war. From this data, we can obtain comprehensive information on the nexus between carbon markets, fossil fuels markets, and renewable energy indices.

Firstly, we chose the Guangdong pilot carbon market in China as our proxy because of its leading position in terms of number of transactions, reflecting its active and robust trading activity. In 2021, the Guangdong ETS proved to be the most active and dynamic market, with a substantial trading volume of 27.13 million units and an impressive turnover of 1.037 billion Chinese yuan. Moreover, the projected increase in Guangdong's carbon emissions to 573.9 million tonnes by 2025 underlines the region's importance in China's efforts to manage carbon emissions and ensure environmental sustainability. This remarkable performance confirms the importance of the Guangdong carbon market among China's regional carbon markets. As the most dynamic and robust market, the Guangdong ETS is a convincing proxy for our study.

Secondly, to represent fossil energy markets, we concentrate on three conventional energy categories, coal (COAL), crude oil (OIL), and natural gas (GAS) markets. Thirdly, we used various clean energy indices from investment websites to represent the performance of the clean energy industry. In addition to the widely recognized S&P Global Clean Energy Index (SPGTCED) and WilderHill Clean Energy Index (ECO), which track all global clean energy sectors, we also included several indices from the NASDAQ OMX Green Economy Index family, which focus on individual sub-sectors of clean energy production. Specifically, we used the NASDAQ OMX Bio/Clean Fuels Index (GRNBIO), Fuel Cell Index (GRNFUEL), Renewable Energy Index (GRNREG), Geothermal Index (GRNGEO), Solar Energy Index (GRNSOLAR) and Wind Energy Index (GRNWIND). This selection of clean energy indices provides a comprehensive analysis of the interconnectedness and impact of volatility between the carbon market and the various segments of the clean energy industry. The description of each utilized variable is provided in Table 1.

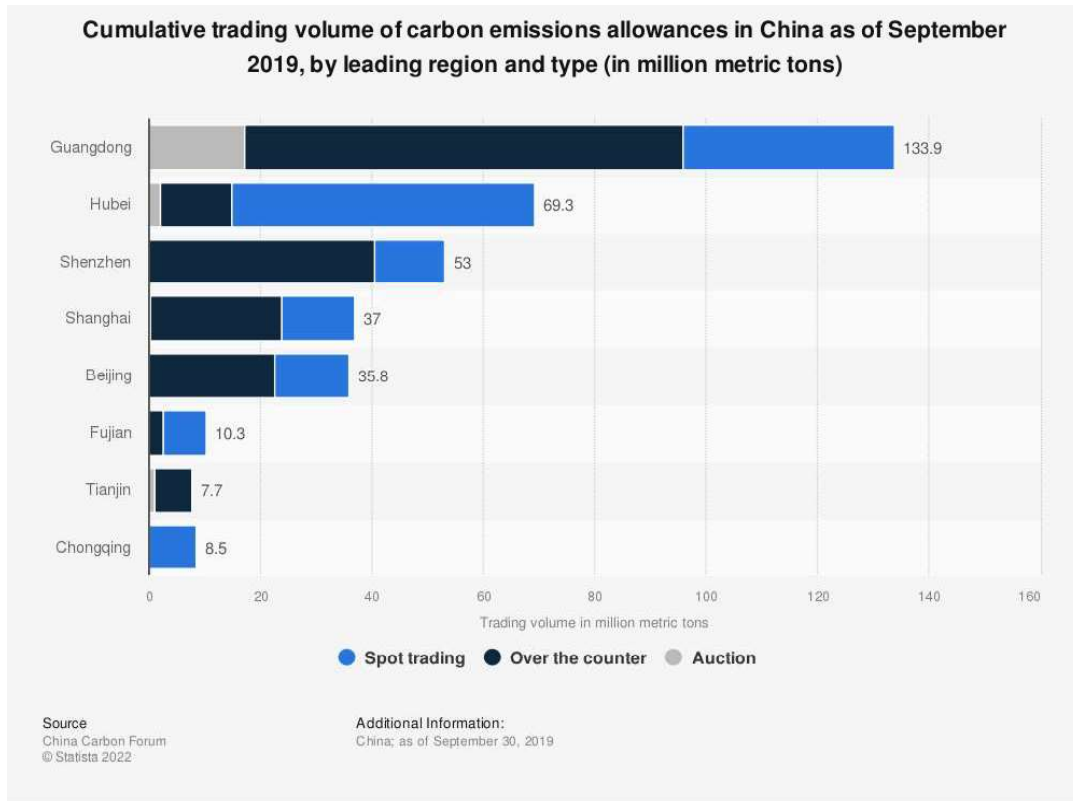


FIGURE 6.2 – trading volume of carbon emissions allowances in china

Table 3 summarizes the descriptive statistics for the logarithmic returns of the variables used. The mean values of all variables remain approximately equal to 0. Similarly, the standard deviations of the carbon and fossil energy indices are still significantly higher than those of the other variables, which suggests that these two indices are more volatile and subject to greater fluctuations in performance. In addition, all variables exhibit negative Skewness, meaning that the tails of the distributions are more pronounced on the left than on the right. In addition, all variables exhibit negative Skewness, meaning that the tails of the distributions are more pronounced on the left than on the right. Oil and coal series show broad-tailed distributions, indicating that extreme values or outliers are more likely to occur in these series. In contrast, the other variable return series show relatively flat-tailed distributions, meaning that returns are more evenly distributed and do not show significant tails. Variable stationarity was assessed using Augmented Dickey-Fuller (ADF) tests. The results indicate that all variables are stationary at the 1% significance level.

6.3.2 Methodology

Our methodology presents two different approaches to examining market interconnections. First, we use Time-Varying Parameter Vector Autoregression (TVP-VAR) to analyze the connectedness of returns. This approach allows us to capture the evolution of relationships between different market returns over time. Second, we use the DCC-

TABLE 6.2 – Data descriptions

	Variable	Definition	Source
European carbon market	EXX EUA	The current market price of European Union Allowances (EUAs) for carbon emissions trading in the spot market, reflecting the cost of emitting one tonne of CO ₂ e in the European carbon market	Thomson reuters data-base
Chinese carbon market	Guangdong carbon price	The current market price of carbon allowances in the Guangdong emissions trading scheme, representing the cost of emitting one tonne of CO ₂ e in the regional carbon market.	Thomson reuters data-base
Fossil fuel energy	Global Oil Price Index	Represents the price index for crude oil, reflecting the average price of oil across different regions or markets worldwide. This index is often used as a benchmark for global oil prices.	Investing website
	Global Coal Price Index (API2 Index)	Represents the price index for coal, which is widely used as a benchmark for thermal coal prices in the international market.	Investing website
	Global Natural Gas Index	Represents the price index for natural gas, reflecting the average price of natural gas across different regions or markets worldwide.	Investing website 15
Clean energy indices	S&P Global Clean Energy Index (SPGTCED)	Tracks the performance of the world's top 100 companies operating in clean energy sectors from both developed and emerging markets.	Investing website
	WilderHill Clean Energy Index (ECO)	The first index that tracks the performance of the top clean energy companies traded on the NASDAQ.	Investing website
	NASDAQ OMX Bio/Clean Fuels Index (GRNBIO)	Tracks the performance of companies operating in the plant-based fuel generation sector.	Investing website
	NASDAQ OMX Renewable Energy Index (GRN-REG)	Tracks the performance of companies operating in renewable energy generation sectors, including solar, wind, geothermal, and fuel cells	Investing website
	NASDAQ OMX Geothermal Index (GRNGEO)	Tracks the performance of companies operating in the geothermal power generation sector.	Investing website
	NASDAQ OMX Fuel Cell Index (GRNFUEL)	Tracks the performance of companies operating in the fuel cell energy sector.	Investing website
	NASDAQ OMX Solar Index (GRNSOLAR)	Tracks the performance of companies operating in the solar energy generation sector.	Investing website
	NASDAQ OMX Wind Index (GRNWIND)	Tracks the performance of companies operating in the wind energy generation sector.	Investing website

TABLE 6.3 – Descriptive statistics of returns

Variable	Mean	Std.Dev	Min	Max	Skewness	Kurtosis	ADF
CarbonEU	0.0253	0.1264	-0.4393	0.3293	-0.6646	4.5221	-11.842***
CarbonCH	0.0036	0.1066	-0.3606	0.3784	-0.3464	5.5740	-7.224***
Oil	-0.0017	0.1357	-0.7819	0.6333	-0.8931	15.1805	-8.346***
Coal	0.0072	0.1082	-0.5047	0.2601	-0.6707	7.3489	-7.183***
GAS	-0.0072	0.1552	-0.5112	0.4168	-0.3737	4.8704	-11.073***
S&PGTCED	0.0071	0.0747	-0.2572	0.1873	-0.1648	3.8276	-9.604***
ECO	0.0019	0.1014	-0.3388	0.3723	-0.0346	4.7683	-10.411***
GRNREGeo	0.0084	0.0519	-0.1435	0.1544	-0.2149	3.7559	-10.910***
GRNBIOre	-0.0010	0.0927	-0.3963	0.2073	-0.8007	5.5406	-10.548***
GRNREGre	0.0084	0.0519	-0.1435	0.1544	-0.2149	3.7559	-10.910***
GRNGEOre	0.0074	0.0784	-0.2732	0.2318	-0.2733	4.2190	-10.785***
GRNFUELre	0.0093	0.1660	-0.3129	0.6096	-0.9163	4.1249	-10.255***
GRNSOLARre	0.0151	0.0881	-0.2721	0.2679	-0.2356	3.4469	-11.375***
GRNWINDre	0.0092	0.0712	-0.2299	0.2166	-0.0810	3.7993	-9.196***

Note : *** indicates the significance level of 1%.

GARCH (Dynamic Conditional Correlation Generalized Autoregressive Conditional Heteroskedasticity) method to study the connectedness of volatility between markets. This technique facilitates the exploration of how volatility transmissions unfold in different markets. In addition, both methods are integrated with the Diebold and Yilmaz (DY) approach, enabling us to analyze the interactions between different markets effectively.

TVP-VAR approach and DY Framework

As mentioned before, in this study, we perform a dynamic spillover analysis using a mixed methodology that combines the DY framework (Diebold and Yilmaz, 2012 ; 2014) with a TVP-VAR model (Koop and Korobilis, 2014). Although the DY framework generates dynamic results with the rolling window method, we opt for the new mixed approach to address the limitations of the rolling window approach. The mixed approach offers three significant advantages. Firstly, it preserves valuable observations. Secondly, the elimination of arbitrary window length selection. Third, robustness to outliers, as highlighted by Antonakakis and Gabauer (2017). To select the best lags in the TVP-VAR model, we use AIC (Akaike Information Criterion), where The lag length is set to one for returns in the European carbon market model and four for the Chinese carbon market model. This methodology has enabled us to examine how the interconnections between carbon market indices and energies have evolved over time, capturing their dynamic interactions and the potential transmission of effects.

We initiate our analysis with a time varying Vector Autoregressive (TVP-VAR) model defined as follow :

$$z_t = B_t z_{t-1} + u_t, \quad u_t \sim N(0, S_t) \quad (6.1)$$

$$vec(B_t) = vec(B_{t-1}) + v_t, v_t \sim N(0, R_t) \quad (6.2)$$

Where z_t and z_{t-1} represent the error term, mu_t are vectors of dimension K . Matrices B_t and S_t have dimensions $n \times n$. The vectorized form of B_t , denoted as $vec(B_t)$, is a column vector with dimensions k^2 . The information available up to time $t - 1$ is represented by rho_{t-1} . The error term γ_t is a column vector with dimensions k^2 , while R_t is a square matrix with dimensions $k^2 \times k^2$. Both S_t and R_t are variance-covariance matrices that change over time.

Diebold and Yilmaz (2009), Diebold and Yilmaz (2012), and Diebold and Yilmaz (2014) propose a connectedness measure that relies on the generalized forecasting error variance decomposition introduced by Koop et al. (1996) and Pesaran and Shin (1998). This measure assesses interconnectedness among variables and is a significant extension of the original technique.

following the approach of Diebold and Yilmaz (2014), the generalized forecast error variance decomposition (GFEVD) is obtained by transforming the time-varying parameter vector autoregressive model (TVP-VAR) into its corresponding vector moving average representation (TVP-VMA) using Wold's theorem. Following the approach of Diebold and Yilmaz (2014), the GFEVD is obtained by considering the specific transformation specified below :

$$z_t = \sum_{i=1}^p B_i z_{t-i} + u_t = \sum_{j=0}^{\infty} A_j u_{t-j} \quad (6.3)$$

The unscaled Generalized Forecast Error Variance Decomposition (GFEVD), denoted as $\Phi_{ij,t}(H)$, is rescaled to ensure that the summation in each row is equal to one. We obtain $\Phi_{ij,t}(H)$, which represents the pairwise directional connectedness between variable j and variable i . It measures the effect of variable j on variable i , considering its contribution to the overall variance of the forecast error. The following steps are used to calculate the above terms :

$$\tilde{\phi}_{ij,t}^g(H) = \frac{S_{ii,t}^{-1} \sum_{t=1}^{H-1} (\iota_i' A_t S_t \iota_j)^2}{\sum_{j=1}^k \sum_{t=1}^{H-1} (\iota_i A_t S_t A_t' \iota_i)} \quad (6.4)$$

$$\tilde{\phi}_{ij,t}^g(H) = \frac{\phi_{ij,t}^g(H)}{\sum_{j=1}^k \phi_{ij,t}^g(H)} \quad (6.5)$$

The selection vector is defined by ι_i where, for the index i , its value is 1 and 0 otherwise. The connectedness measures are then obtained from the work of Diebold and Yilmaz (2012, 2014), as follows :

$$TO_{jt} = \sum_{i=1, i \neq j}^k \tilde{\phi}_{ij,t}^g(H) \quad (6.6)$$

$$FROM_{jt} = \sum_{i=1, i \neq j}^k \tilde{\phi}_{ji,t}^g(H) \quad (6.7)$$

$$NET_{jt} = TO_{jt} - FROM_{jt} \quad (6.8)$$

$$TCI_t = k^{-1} \sum_{j=1}^k TO_{jt} \equiv k^{-1} \sum_{j=1}^k FROM_{jt} \quad (6.9)$$

Equation (6) provides a measure of the total directional connectedness from the variable j to all other variables in the network. Equation (7) represents the total directional connectedness to the variable j from all other variables in the system. Equation (8) is the difference between equations (6) and (7), indicating the total net directional connectedness associated with the variable j . For instance, if $NET_{jt} > 0$, this would mean that j is a net driver of the network as it is primarily involved in transmitting shocks. Equation (10) is an aggregated measure of the total connectedness among all the variables in the network and seeks to serve as a proxy for the overall interconnectedness and potential market vulnerability. A greater total connectedness index (TCI) indicates that a shock to a specific variable significantly affects the entire network, thus increasing the associated market risk. Conversely, a smaller TCI indicates a reduced level of connectedness, meaning that other variables in the network are not significantly affected by shocks to a particular variable, resulting in lower overall market risk.

DCC-GARCH approach and DY Framework

In this part we describe the DCC-GARCH method for determining volatility interconnections within a time series network. First introduced by Engle (2002), the DCC-GARCH method is used to model time-varying conditional variances and covariances within a given time-series network. The model specification is as follows :

$$x_t = \mu_t + \varepsilon_t \quad \varepsilon_t \sim \mathcal{N}(0, H_t) \quad (6.10)$$

$$h_t = \alpha_0 + \alpha_1 \theta_{t-1}^2 + \beta_2 h_{t-1} \quad (6.11)$$

$$H_t = D_t R_t D_t \quad (6.12)$$

$$D_t = \text{diag} \left[h_{1t}^{1/2}, h_{2t}^{1/2} \right] \quad (6.13)$$

$$R_t = \text{diag} [Q_t]^{-1/2} Q_t \text{diag} [Q_t]^{-1/2} \quad (6.14)$$

Where D_t corresponds to the time-varying conditional variances, and R_t represents the dynamic conditional

correlations. Both matrices have dimensions of $m \times m$. Moreover, μ_t denotes the conditional means, and u_t signifies the standardized error residuals, each exhibiting dimensions of $m \times 1$. In the case of each individual series, D_t is characterized by GARCH models, in accordance with Bollerslev's (1986) framework. Notably, the integration of persistence and shock parameters aligns with the recommendations proposed by Hansen and Lunde (2005).

Q_t denotes the positive definite matrix composed of $q_{12,t}$ elements, and h_t represents the conditional standard deviations. Based on these elements, we can formulate the estimated DCC model as follows :

$$Q_t = (1 - a - b)\bar{Q} + au_{t-1}u_{t-1}^T + bQ_{t-1} \quad (6.15)$$

Where the parameters a and b are non-negative scalars that must satisfy the condition $a + b < 1$. The matrix \bar{Q} represents the unconditional variance matrix of the standardized residuals u_t . Therefore, we can write the dynamic conditional correlations series as follows :

$$\rho_{12,t} = \frac{q_{12,t}}{\sqrt{q_{11,t} \cdot q_{22,t}}} \quad (6.16)$$

6.4 Results and recommendations

6.4.1 Return Spillovers

Tables 4 and 5 present the results of dynamic connectedness measures obtained from the time-varying parameter vector autoregression (TVP-VAR) model. These tables show the average connectedness measures, illustrating the spillover effects of returns on all markets within the networks for Europe and China, respectively. As indicated in the data section, we used an optimal lead time of 1 for the European model and 4 for the Chinese model, determined using two criteria : Akaike's information criterion (AIC) and final prediction error (FPE), a VAR model was estimated over a specific window, and then the spillover index was calculated. Based on our data, we chose a rolling window of 110 days ($w = 110$) with a step of 1 month.

The results reveal that the average dynamic connectivity of total returns between January 2014 and April 2023 is 62.42% for Europe and 76.11% for China, indicating not only that the level of connectivity is high in both regions but also that China has a higher average level of connectivity than Europe. These results can be attributed to factors such as China's rapid economic growth and rising energy demand induced by its manufacturing and industrial sectors, potential differences in government policies, and investor behavior. These factors contribute to the stronger correlations observed between carbon and energy markets, underlining the complex interplay of economic, political and market dynamics that shape their patterns of connectivity.

In Figures 2 and 3, total return connectedness network diagrams reveal distinct connectedness patterns between carbon markets and energy market indices in Europe and China. Figure 1, which focuses on Europe, reveals that

the European carbon market is linked to three clean energy indices (GRNSOLAR, ECO, SPGTCED), all displaying connections with the oil price. In addition, all clean energy indices show links with the oil price, except the GRNFUEL index. By contrast, Figure 2, which shows the Chinese connectedness network, presents a more complex connectivity landscape. The Chinese carbon market shows a higher degree of connectivity with various other markets, particularly clean indices closely linked to fossil fuel markets. Furthermore, the graphs, in line with the figures, highlight that coal price returns contribute significantly to carbon price fluctuations among fossil fuels. This result corroborates the study conducted by Wu et al. (2020).

These distinct interconnectedness patterns can be attributed to many determining factors. In Europe, the relatively direct link between the carbon market and three clean energy indices, which are then linked to oil prices, could reflect the region's focus on transitioning to cleaner energy sources and reducing carbon emissions. This focus could lead to stronger links between renewable energy markets and oil prices, as similar policies and market dynamics influence these markets. Given that the GRNFUEL index tracks the performance of companies in the fuel cell energy sector, the weak connectedness between this index and oil prices could be attributed to the specific dynamics of the fuel cell industry. Fuel cells are a distinct technology in the energy sector, relying on hydrogen and other renewable sources rather than traditional fossil fuels such as oil. This technological distinction may explain why there is no direct link between the GRNFUEL index and oil price, as drivers and market influences can be very different.

In contrast, the country's developing economy may influence the more complex interconnectedness pattern observed in the Chinese network. The Chinese carbon market appears to be linked to various other markets, suggesting a complex interplay of factors influencing its dynamics. The close links between green indices and fossil fuel markets could indicate that China is still relying on traditional energy sources for its rapid economic growth while at the same time investing in and promoting green technologies. This complex interconnectedness could reflect the country's efforts to balance economic expansion and environmental sustainability, leading to closer relations between the various energy sectors. Furthermore, the TO and FROM connectedness results reveal that clean energy indices play a crucial role as key drivers of spillovers impacting various markets, including fossil fuel and carbon markets, in both regions.

Figures 3 and 4 illustrate the dynamic time-varying returns spillover between different markets in Europe and China, respectively. In particular, there is a slight increase in total connexity between returns at the start of 2020, corresponding to an increase in market connectedness. That coincides with the period of the COVID-19 crisis, suggesting its influence on market dynamics and interconnectedness. This result is consistent with the study by (Jiang et al., 2023).

Figures 9 and 10 show that the connectedness of total net returns for Europe and China indicates that the carbon market in both regions tends to be a net receiver of shock, suggesting that external influences significantly

determine their returns. In Europe, the graph shows a shift from a net connectedness of -50 in 2014 to -10 today, implying less dependence on systemic shocks over time.

6.4.2 Volatility Spillovers

The next step in the analysis is to assess the interconnections of the carbon and energy markets using the volatility spillover framework. For this purpose, a DCC-GARCH model (Gauber, 2020) is used. Volatility series were determined using the conventional GARCH(1,1). The selection of an optimal lag order of 1, for the two models, was determined by the AIC criterion. As shown in Table 5, the average total dynamic volatility correlation over the period from January 2014 to April 2023 is 50.89% for Europe and 47.03% for China. Notably, these values are slightly lower and distinct in relation to the connectedness of returns.

Figures 11 and 12 illustrate the evolution of total dynamic volatility on the European and Chinese markets. It is clearly apparent that the spread of global volatility has remained stable over the selected period in both regions. This stability is particularly remarkable when major global events such as the oil crash, the COVID-19 pandemic and the Russian-Ukrainian war are taken into account. The resilience of indices through diversification and adaptation to shocks has contributed to this enduring stability, underlining the need for ongoing monitoring to assess their reaction to future developments.

In the European context, The observed volatility spillover values, as described in Table 4 and Figure 3, indicate a dominant outflow from several clean energy indices, notably ECO, S&P GTCED, GRNFUEL, GRNREG and GRNGEO. Conversely, GRNBIO, GRNSOLAR, and GRNWIND are the recipients of these spillover effects. As far as fossil fuels are concerned, oil and coal are the transmitters of spillover effects, while gas is the recipient. The impact of the carbon market on other markets is particularly low (1.41%). However, the spillover value from the system to the European carbon market is higher (47.71%). This dynamic suggests that the carbon market is a net receiver of shocks. In addition, the clean energy sector presents a complex transmission and reception pattern. These interconnected dynamics highlight the complex relationships between different sectors and underline the need for appropriate risk management strategies.

In the context of China, there is a distinct pattern where some clean energy indices, in particular ECO, S&PGTCED, GRNFUEL and GRNGEO, play an important role in transmitting volatility spillovers to other markets. Conversely, GRNBIO, GRNSOLAR, GRNWIND and GRNREG appear to be the recipients of these spillovers. Notably, among fossil fuels, oil and coal appear to be spillover transmitters, while gas acts as a spillover receiver. The strong interconnectedness of clean energy indices is demonstrated in the analysis. Specifically, GRNWIND, GRNSOLAR, and GRNBIO prove to be recipients of volatility spillovers from other clean energy indices, in particular the ECO index. Specifically, ECO is the leading index tracking the performance of leading NASDAQ-listed clean energy companies, significantly contributing to these spillover effects. While ECO impacts the European carbon market, it does not

exert the same influence on the Chinese market, suggesting regional disparities in its effects. These variations can probably be explained by differences in market dynamics and the composition of influential clean energy companies in each region.

6.5 Conclusion

This paper investigated the interconnectedness between carbon markets, fossil fuels, and major renewable energy indices in Europe and China. This study also highlighted the complex interactions between economic, regulatory, and environmental factors that influence the dynamics between these regions' carbon markets, fossil fuel markets, and renewable energy indices.

The interconnectedness of these markets was investigated by assessing and establishing the effects resulting from the transmission of returns and volatility. To achieve this, we used the TVP-VAR method, as used by Antonakakis and Gabauer (2017), to quantify the impacts of return and volatility transmissions. In addition, we used the DCC-GARCH technique developed by Gabauer (2020) to examine the propagation of volatility impacts. These methodologies were combined with the connectedness framework by Diebold and Yilmaz (2014) to provide a more accurate and nuanced understanding of how return and volatility transmissions evolve over time, leading to improved risk assessment, policy insights, and forecasting capabilities.

The findings regarding return spillover analysis revealed that both the European and Chinese carbon markets exhibit characteristics of being net recipients of influences from other market sectors. We found that the European carbon market demonstrates a unique pattern where renewable energy markets, devoid of direct associations with fossil fuel sectors, primarily influence its EUETS returns. Conversely, the carbon market experiences a more intricate network of influences within the Chinese market context, encompassing both renewable and non-renewable energy domains. Notably, our results reveal that gas price returns directly impact the carbon market in the Chinese network. In contrast, oil and coal prices indirectly impact the carbon market as they propagate their influence via the gas market, contributing to a multi-layered web of interactions within the Chinese carbon market's return dynamics.

The results of volatility spillover effects show that the European carbon market receives volatility from three clean energy market indices, including ECO, GRNREG, and GRNSOLAR. In contrast, there are no significant spillover effects from oil, gas, or coal within this network. The Chinese carbon market shows a similar lack of discernible spillover effects. By comparing the dynamics of volatility transfers between the European and Chinese carbon markets, distinct patterns emerge. In Europe, the carbon market is influenced by volatility from major clean and renewable energy market indices. However, the absence of spillover effects from oil, gas, and coal indicates a relative isolation of the carbon market from the volatility of fossil fuel markets. These results could be attributed to efforts to decouple carbon market behavior from fossil fuel fluctuations as part of sustainability and climate awareness strategies.

The lack of spillover effects from renewable energy and fossil fuel markets to the Chinese carbon market calls for

targeted strategies to ensure a balanced and sustainable energy landscape. First and foremost, policymakers should prioritize the establishment of clear and coherent regulatory frameworks governing interactions between the carbon, renewables and fossil fuel sectors. Regulatory clarity will promote transparency and predictability and create an environment conducive to cross-sector collaboration and sustainable growth. Secondly, given the relatively immature state of the Chinese carbon market, efforts should be made to ensure its robust development. This may include initiatives to expand market participation, strengthen infrastructure, and improve the transparency of carbon pricing mechanisms. Sustained monitoring, evaluation, and research are essential to keep up with developments in the market and ensure that policies evolve in line with the dynamics of China's energy landscape. By investing in capacity building and developing a comprehensive transition plan, policymakers can guide China towards a sustainable energy mix that aligns with global environmental goals.

The contrasting pattern of volatility spillovers in the European context underlines the importance of targeted recommendations. Policymakers should consider initiatives strengthening the link between these two sectors to take advantage of the impact of volatility in clean energy markets on the European carbon market. This could involve developing mechanisms that reward cleaner energy production and incentivize engagement in the carbon market, thereby strengthening the role of renewables in carbon mitigation strategies. Furthermore, although fossil fuels have little impact on the European carbon market, efforts should be made to ensure the resilience of fossil fuel markets.

In China, as in Europe, investors need to keep a close eye on regulatory developments in the carbon, clean energy, and fossil fuel sectors, as political developments can considerably impact market dynamics. In China, where the carbon market is maturing, a patient, long-term approach to investment is recommended, taking into account the potential maturation of the market and diversified portfolios that balance exposure to the clean energy and fossil fuel sectors. Adopting sustainable investments aligned with China's environmental commitments can offer favorable returns and support broader sustainability goals. In Europe, investment strategies can be optimized by capitalizing on returns from integrating clean energy assets into portfolios and by keeping an eye on trends in carbon pricing. Diversification across sectors, while keeping up with changing policy and industry trends, remains essential to effectively and efficiently navigate the complex energy landscape of both regions.

In conclusion, this study is particularly relevant given the contrasting positions of China and Europe in terms of emissions and energy consumption. With regards to China, it is as a major carbon emitter and energy consumer, presenting a unique set of challenges and opportunities for sustainable practices and policy actions. When looking at Europe, its progress towards its sustainable goals opens the way for insightful comparison, enabling us to learn from their advances. By highlighting these relationships, this study contributes to a comprehensive understanding of market interactions and their wider implications for sustainable development, that is aligned with Europe's progress and that also addresses China's energy consumption and emissions challenges.

Appendix

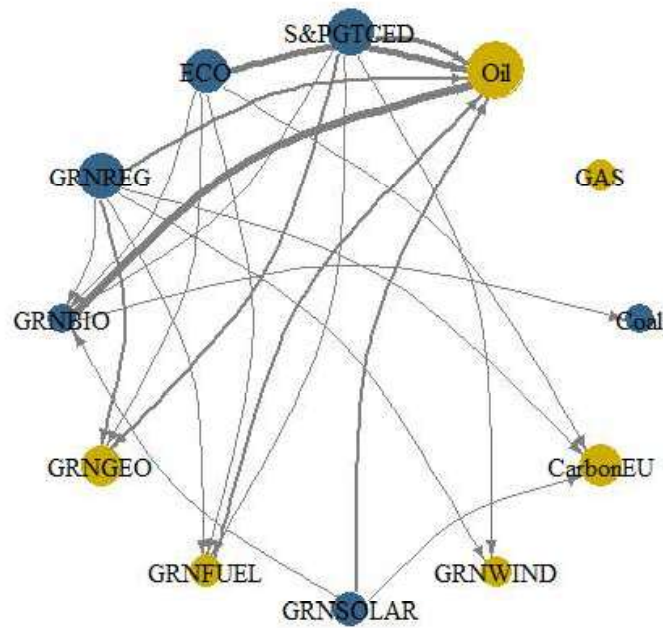


FIGURE 6.3 – Net Pairwise Dynamic Connectedness in Europe

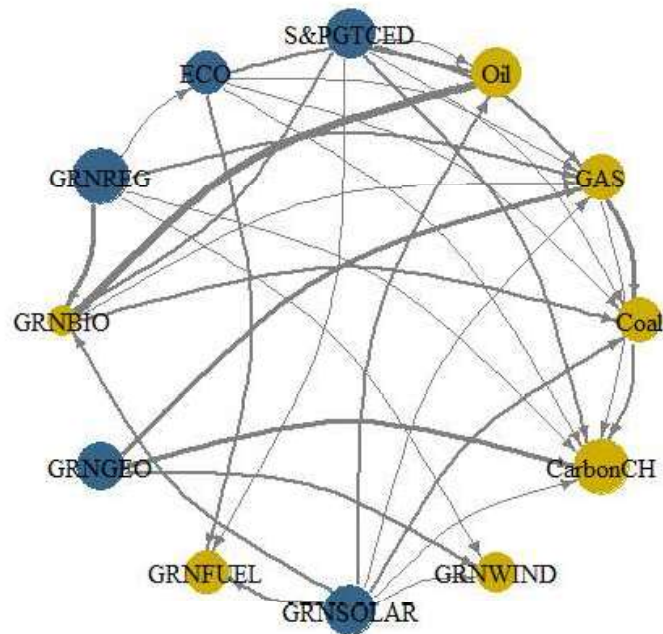


FIGURE 6.4 – Net Pairwise Dynamic Connectedness in China

Note : Blue nodes signify the senders of net shocks, while yellow nodes indicate the receivers. The size of the nodes is proportionate to the absolute values of the NET connectedness index. Arrows between nodes depict the direction of spillovers between variables, and the thickness of these arrows signifies the strength of the spillovers.

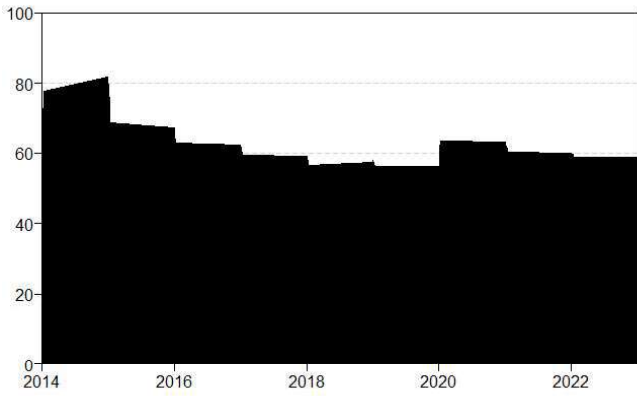


FIGURE 6.5 – Total Connectedness Index in Europe

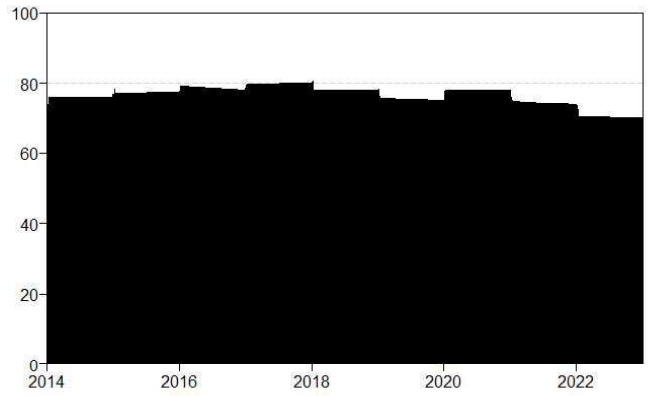


FIGURE 6.6 – Total Connectedness Index in China

FIGURE 6.7 – Return connectedness

TABLE 6.4 – Average dynamic total return connectedness for Europe

	Coal	GAS	Oil	S&PGTCED	ECO	GRNREG	GRNBIO	GRNGEO	GRNFUEL	GRNSOLAR	GRNWIND	CarbonEU	FROM
Coal	74.46	4.51	2.80	1.92	1.19	1.78	5.54	1.45	1.32	1.10	2.18	1.74	25.54
GAS	3.28	64.27	4.20	3.62	4.25	3.04	5.25	0.98	2.46	2.23	2.80	3.63	35.73
Oil	2.45	3.38	35.33	7.58	9.82	5.41	14.14	1.85	6.91	7.43	3.58	2.11	64.67
S&PGTCED	1.52	2.39	0.80	20.70	14.01	15.28	8.16	6.31	6.91	12.08	10.48	1.37	79.30
ECO	1.42	2.18	0.84	15.17	24.00	11.61	7.90	4.52	10.90	14.70	5.69	1.06	76.00
GRNREG	1.57	1.56	0.79	15.47	11.17	20.52	7.90	7.97	6.77	13.28	11.54	1.47	79.48
GRNBIO	2.72	4.02	2.97	11.73	11.43	11.36	29.68	3.76	5.88	9.37	5.00	2.08	70.32
GRNGEO	2.03	2.66	0.91	10.95	7.89	13.33	4.23	34.30	7.56	6.76	8.50	0.86	65.70
GRNFUEL	1.40	1.21	1.53	10.95	13.88	10.79	5.40	7.67	32.29	7.66	6.72	0.51	67.71
GRNSOLAR	2.58	1.90	0.77	14.02	15.76	15.17	6.38	4.29	6.41	24.03	7.50	1.18	75.97
GRNWIND	3.83	2.20	0.88	14.60	6.33	15.75	4.71	7.72	4.49	8.75	29.23	1.52	70.77
CarbonEU	3.86	3.56	1.70	3.61	5.34	4.71	2.27	1.67	2.50	4.27	4.30	62.21	37.79
TO	26.65	29.57	18.18	109.62	101.07	108.22	71.89	48.19	62.11	87.65	68.30	17.53	748.99
Inc.Own	101.11	93.85	53.51	130.32	125.07	128.74	101.56	82.49	94.39	111.68	97.53	79.74	TOTAL
NET	1.11	-6.15	-46.49	30.32	25.07	28.74	1.56	-17.51	-5.61	11.68	-2.47	-20.26	62.42

TABLE 6.5 – Average dynamic total return connectedness for China

	Coal	GAS	Oil	S&PGTCED	ECO	GRNREG	GRNBIO	GRNGEO	GRNFUEL	GRNSOLAR	GRNWIND	CarbonCH	FROM
Coal	36.09	11.53	4.74	4.56	4.97	5.77	7.4	5.34	3.49	7.61	3.77	4.73	63.91
GAS	4.77	25.47	6.76	8.13	6.02	8.87	6.34	9.28	5.69	6.74	5.63	6.3	74.53
Oil	5.5	5.27	31.64	4.88	6.75	5.51	12.76	7.57	4.82	6.62	3.32	5.34	68.36
S&PGTCED	1.99	3.95	2.59	18.65	13.12	14.62	8.21	8.25	5.34	12.29	8.99	1.99	81.35
ECO	2.59	3.63	2.32	13.82	19.41	11.88	8.66	7.21	8	14.01	5.92	2.55	80.59
GRNREG	3.99	3.47	4.9	12.66	9.13	16.94	6.24	11.85	6.49	13.09	9.45	1.8	83.06
GRNBIO	3.53	3.01	3.67	12.54	10.68	12.21	20.26	7.93	5.94	10.81	6.04	3.38	79.74
GRNGEO	4.44	3.74	6.43	8.79	6.58	13.99	5.74	26.42	4.63	8.12	6.73	4.4	73.58
GRNFUEL	4.85	3.93	3.98	8.35	12.16	8.09	5.91	6.78	25.2	9.34	5.71	5.69	74.8
GRNSOLAR	2.83	3.91	2.34	13.06	13.84	15	5.73	8.73	4.78	19.13	8.01	2.63	80.87
GRNWIND	3.46	4.21	3.9	11.17	7.89	13.08	6.88	11.42	4.22	11.61	18.84	3.3	81.16
CarbonCH	9.11	9.23	4.45	7.02	5.95	5.11	4.74	10.05	4.82	5.68	5.21	28.63	71.37
TO	47.07	55.88	46.08	104.98	97.1	114.15	78.6	94.43	58.24	105.91	68.78	42.12	913.32
Inc.Own	83.16	81.35	77.72	123.62	116.5	131.09	98.86	120.85	83.44	125.04	87.62	70.75	TOTAL
NET	-16.84	-18.65	-22.28	23.62	16.5	31.09	-1.14	20.85	-16.56	25.04	-12.38	-29.25	76.11

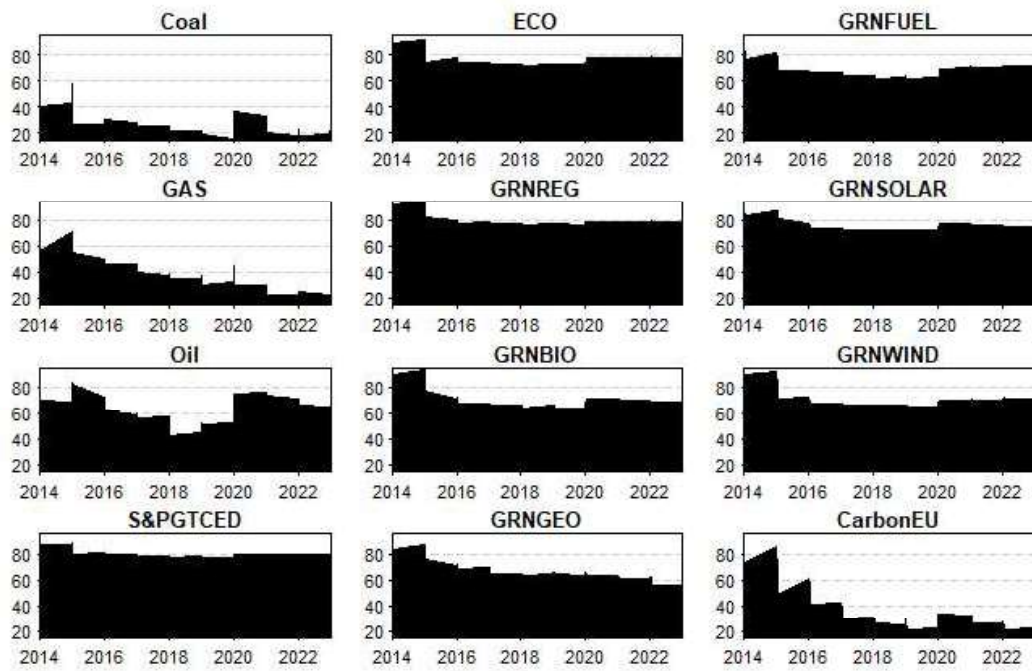


FIGURE 6.8 – Europe : Dynamic directional return connectedness FROM others

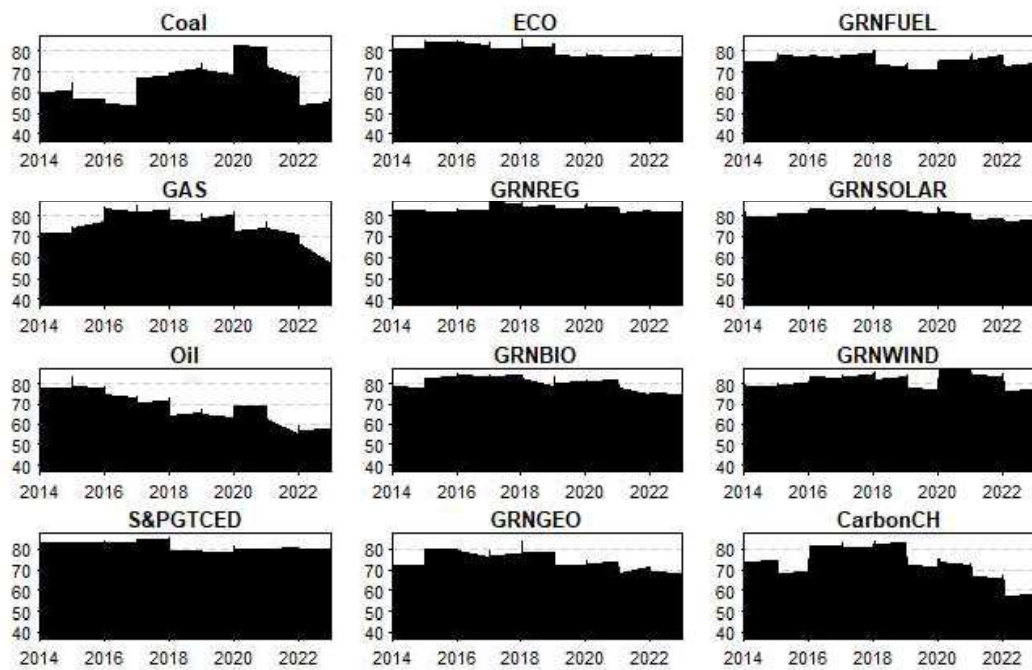


FIGURE 6.9 – China : Dynamic directional return connectedness FROM others

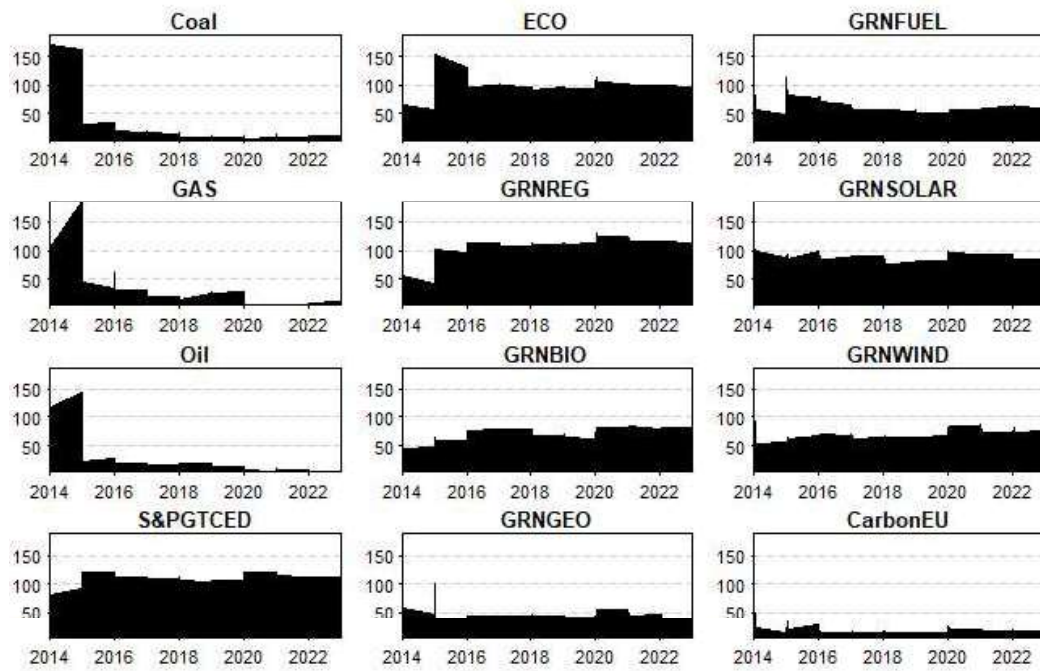


FIGURE 6.10 – Europe : Dynamic directional return connectedness FROM others

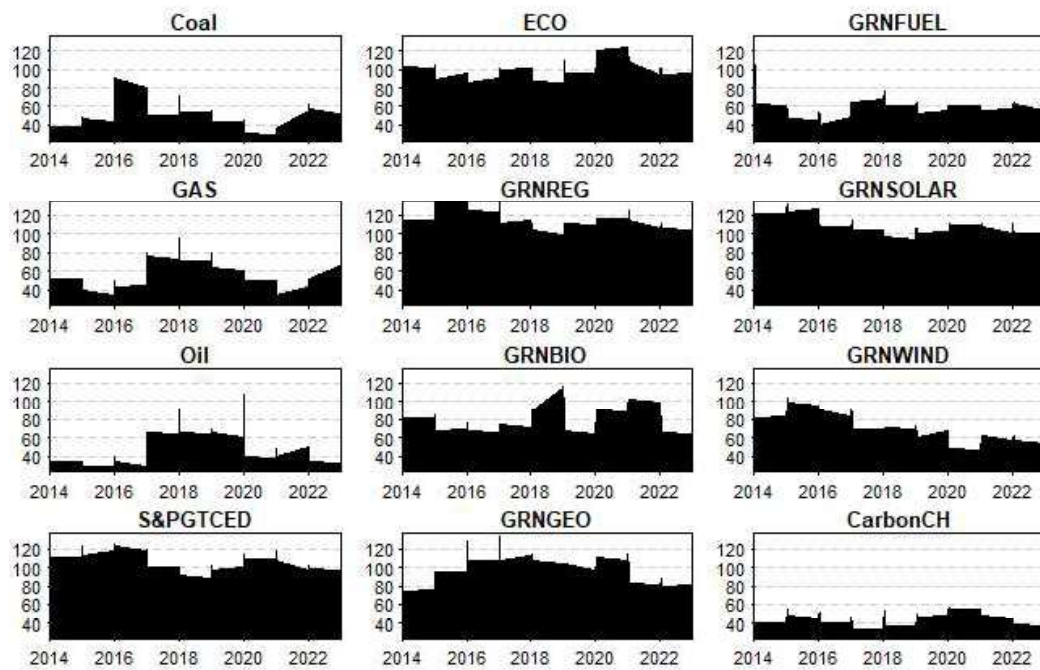


FIGURE 6.11 – China : Dynamic directional return connectedness FROM others

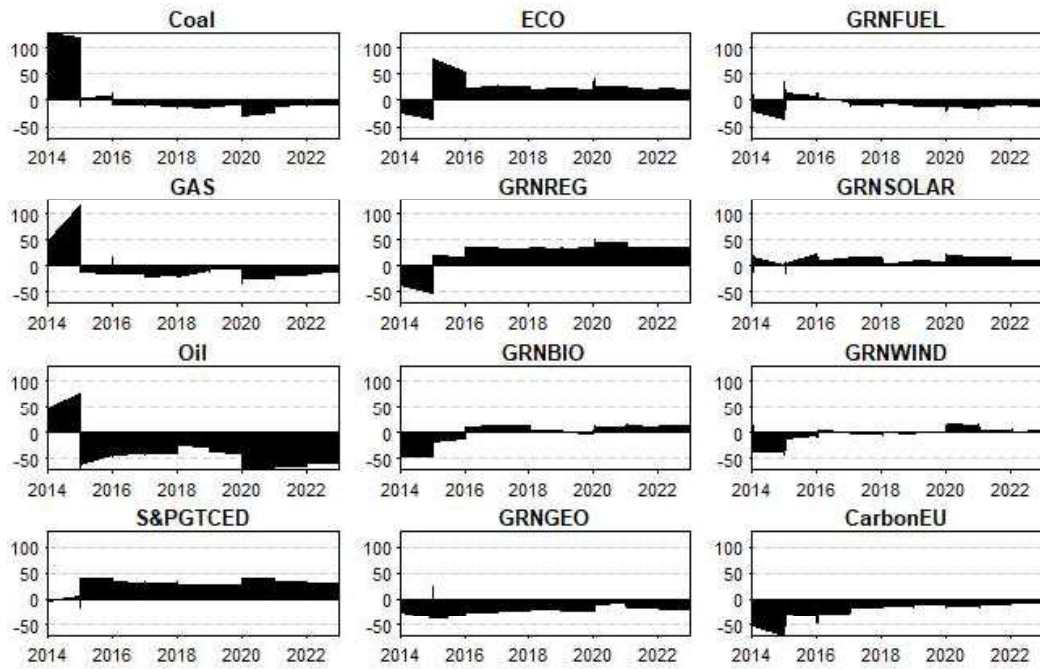


FIGURE 6.12 – Europe : Total net return connectedness

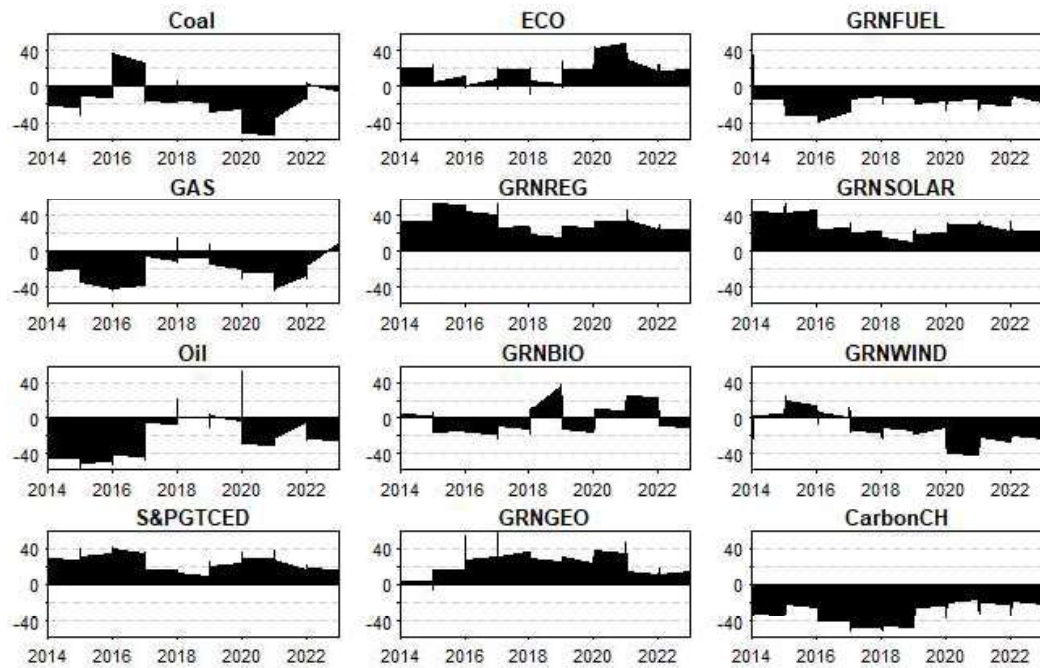


FIGURE 6.13 – China : Total net return connectedness

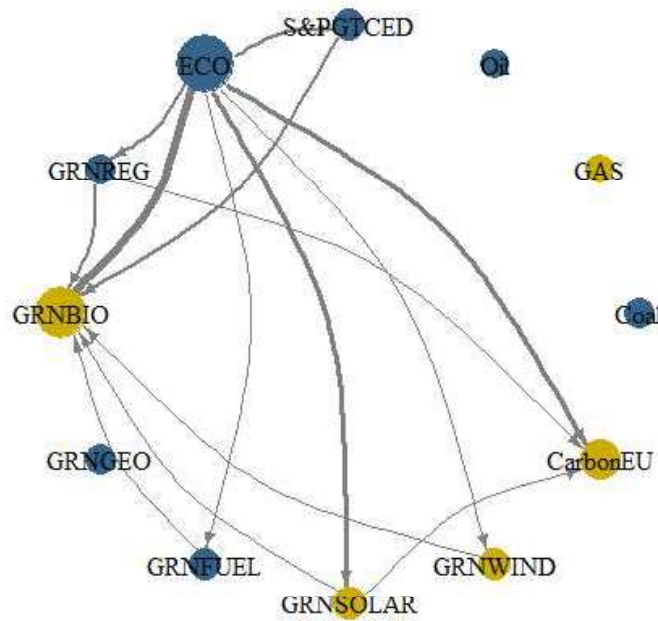


FIGURE 6.14 – Dynamic total volatility connectedness : Europe

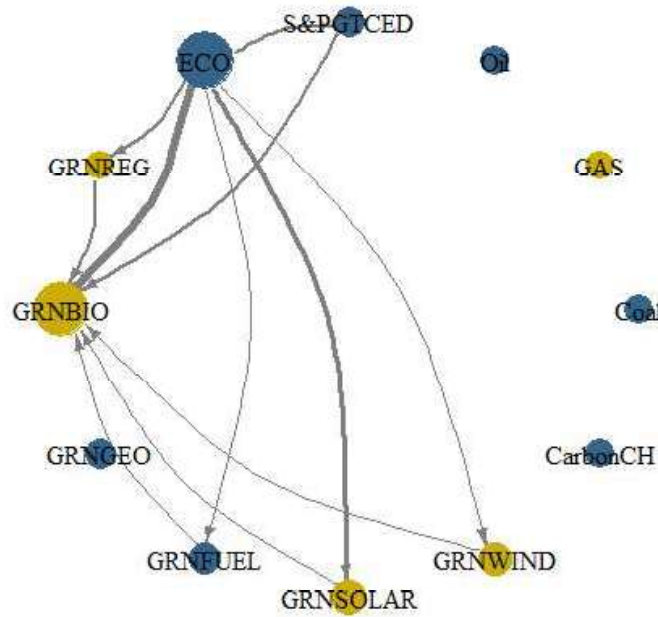


FIGURE 6.15 – Dynamic total volatility connectedness : China

Note : Blue nodes signify the senders of net shocks, while yellow nodes indicate the receivers. The size of the nodes is proportionate to the absolute values of the NET connectedness index. Arrows between nodes depict the direction of spillovers between variables, and the thickness of these arrows signifies the strength of the spillovers.

TABLE 6.6 – Average dynamic total volatility connectedness for Europe

Coal	94.13	0.45	4.91	0.03	0.14	0.02	0.05	0.01	0.17	0.01	0.17	0.01	0.04	0.04	5.87
GAS	1.53	96.25	0.05	0.42	1.27	0.01	0.19	0.00	0.27	0.00	0.27	0.00	0.01	0.01	3.75
Oil	3.54	0.01	95.67	0.05	0.05	0.02	0.01	0.39	0.25	0.00	0.25	0.00	0.01	0.00	4.33
S&PGTCED	0.09	0.33	0.20	20.41	27.38	13.98	1.27	6.91	9.35	9.72	9.72	10.25	10.25	0.14	79.59
ECO	0.18	0.49	0.09	13.58	41.63	9.36	1.16	4.63	14.30	9.57	9.57	4.80	4.80	0.20	58.37
GRNREG	0.05	0.01	0.10	16.01	21.60	19.31	1.38	8.51	8.91	11.27	11.27	12.65	12.65	0.21	80.69
GRNBIO	1.59	1.71	0.49	14.69	27.11	14.02	7.22	3.72	10.00	9.74	9.74	9.36	9.36	0.35	92.78
GRNGEO	0.01	0.00	1.13	5.62	7.59	6.04	0.26	67.28	6.06	2.03	2.03	3.97	3.97	0.01	32.72
GRNFUEL	0.36	0.17	0.72	7.51	23.11	6.26	0.69	5.99	45.47	5.33	5.33	4.35	4.35	0.05	54.53
GRNSOLAR	0.03	0.00	0.00	14.22	28.24	14.41	1.23	3.66	9.72	20.02	20.02	8.18	8.18	0.29	79.98
GRNWIND	0.15	0.01	0.04	15.07	14.24	16.24	1.19	7.17	7.96	8.22	8.22	29.60	29.60	0.13	70.40
CarbonEure	3.77	0.25	0.05	5.31	16.22	7.25	1.18	0.34	2.26	7.68	7.68	3.40	3.40	52.29	47.71
TO	11.30	3.43	7.77	92.52	166.95	87.58	8.61	41.33	69.24	63.57	63.57	57.01	57.01	1.41	610.71
Inc.Own	105.43	99.67	103.44	112.93	208.58	106.89	15.83	108.61	114.71	83.59	83.59	86.61	86.61	53.71	TCl
NET	5.43	-0.33	3.44	12.93	108.58	6.89	-84.17	8.61	14.71	-16.41	-16.41	-13.39	-13.39	-46.29	50.89

TABLE 6.7 – Average dynamic total volatility connectedness for China

Coal	93.73	0.45	4.89	0.03	0.14	0.02	0.05	0.01	0.17	0.01	0.17	0.01	0.04	0.47	6.27
GAS	1.53	96.23	0.05	0.42	1.27	0.01	0.19	0.00	0.27	0.00	0.27	0.00	0.01	0.02	3.77
Oil	3.54	0.01	95.67	0.05	0.05	0.02	0.01	0.39	0.25	0.00	0.25	0.00	0.01	0.00	4.33
S&PGTCED	0.09	0.33	0.20	20.43	27.41	13.99	1.27	6.92	9.36	9.73	9.73	10.26	10.26	0.02	79.57
ECO	0.18	0.49	0.09	13.61	41.71	9.38	1.16	4.64	14.33	9.59	9.59	4.81	4.81	0.00	58.29
GRNREG	0.05	0.01	0.10	16.02	21.62	19.32	1.38	8.51	8.92	11.28	11.28	12.65	12.65	0.14	80.68
GRNBIO	1.59	1.72	0.49	14.73	27.18	14.06	7.24	3.73	10.03	9.77	9.77	9.39	9.39	0.06	92.76
GRNGEO	0.01	0.00	1.13	5.61	7.58	6.03	0.26	67.16	6.05	2.03	2.03	3.96	3.96	0.18	32.84
GRNFUEL	0.36	0.17	0.72	7.51	23.12	6.26	0.69	6.00	45.48	5.33	5.33	4.35	4.35	0.00	54.52
GRNSOLAR	0.03	0.00	0.00	14.25	28.30	14.44	1.23	3.67	9.75	20.06	20.06	8.20	8.20	0.06	79.94
GRNWIND	0.14	0.01	0.04	15.05	14.22	16.21	1.18	7.16	7.95	8.21	8.21	29.56	29.56	0.27	70.44
CarbonCH	0.60	0.01	0.00	0.01	14.22	16.21	0.00	0.11	0.00	0.02	0.02	0.09	0.09	99.09	0.91
TO	8.13	3.19	7.70	87.29	150.90	80.48	7.43	41.13	67.09	55.96	55.96	53.77	53.77	1.23	564.31
Inc.Own	101.86	99.42	103.37	107.73	192.61	99.80	14.68	108.29	112.57	76.03	76.03	83.33	83.33	100.32	TCl
NET	1.86	-0.58	3.37	7.73	92.61	-0.20	-85.32	8.29	12.57	-23.97	-23.97	-16.67	-16.67	0.32	47.03

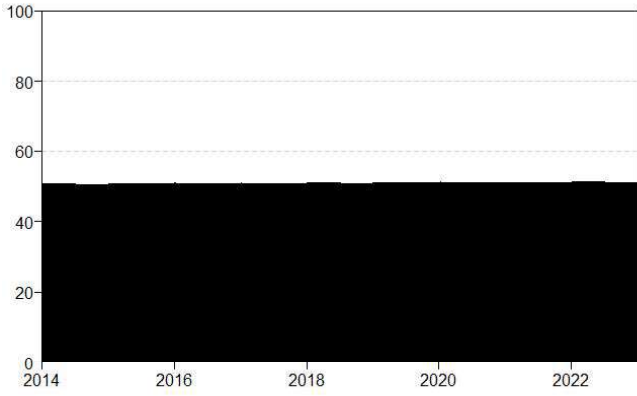


FIGURE 6.16 – Total Connectedness Index in Europe

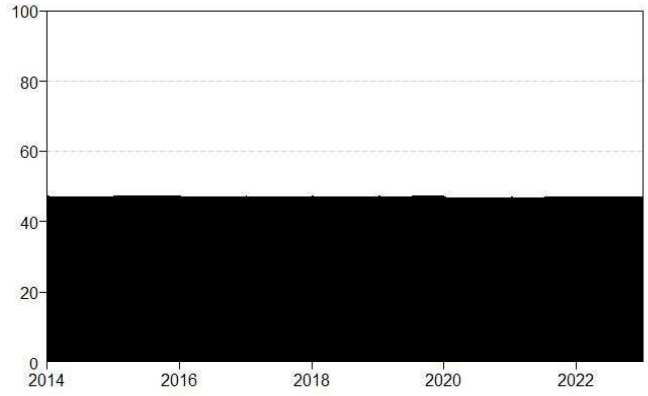


FIGURE 6.17 – Total Connectedness Index in China

FIGURE 6.18 – Volatility connectedness

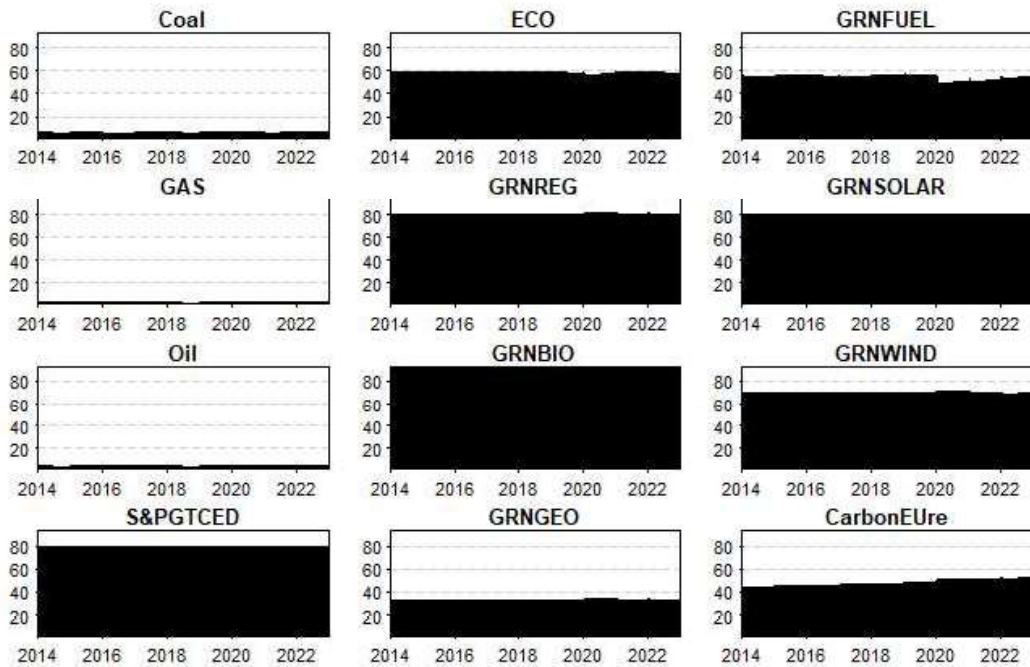


FIGURE 6.19 – Dynamic directional volatility connectedness FROM others : Europe

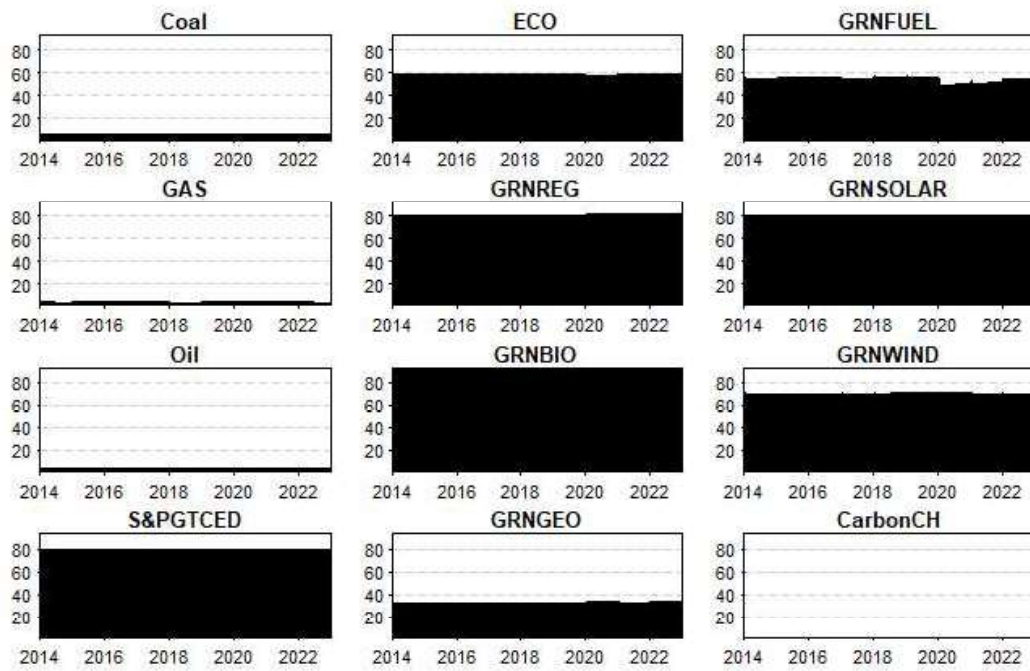


FIGURE 6.20 – Dynamic directional volatility connectedness FROM others : China

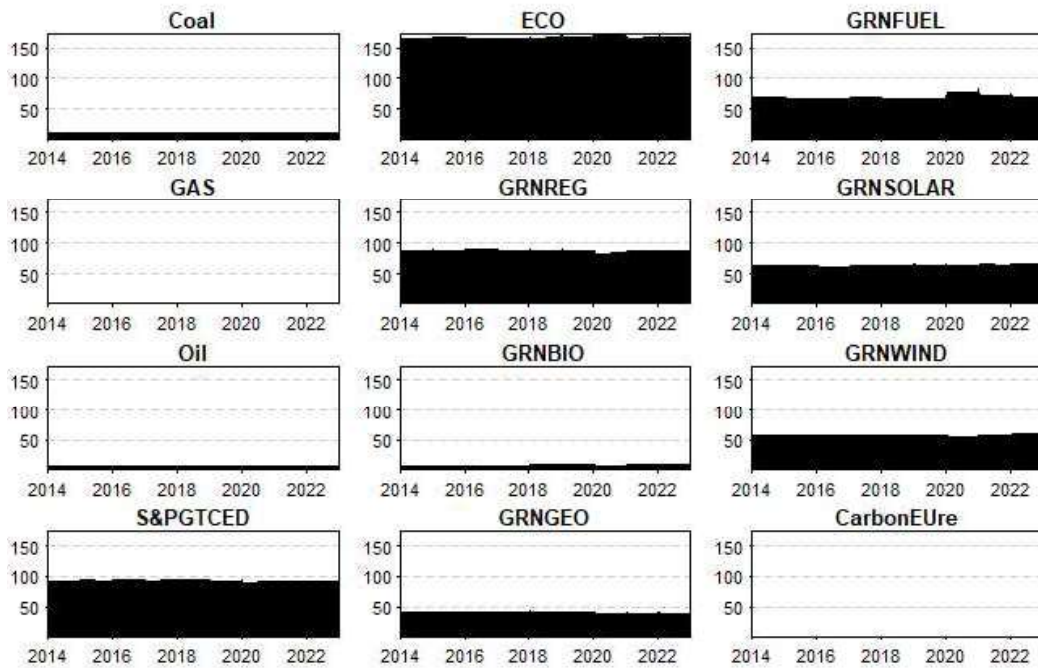


FIGURE 6.21 – Dynamic directional volatility connectedness TO others : Europe

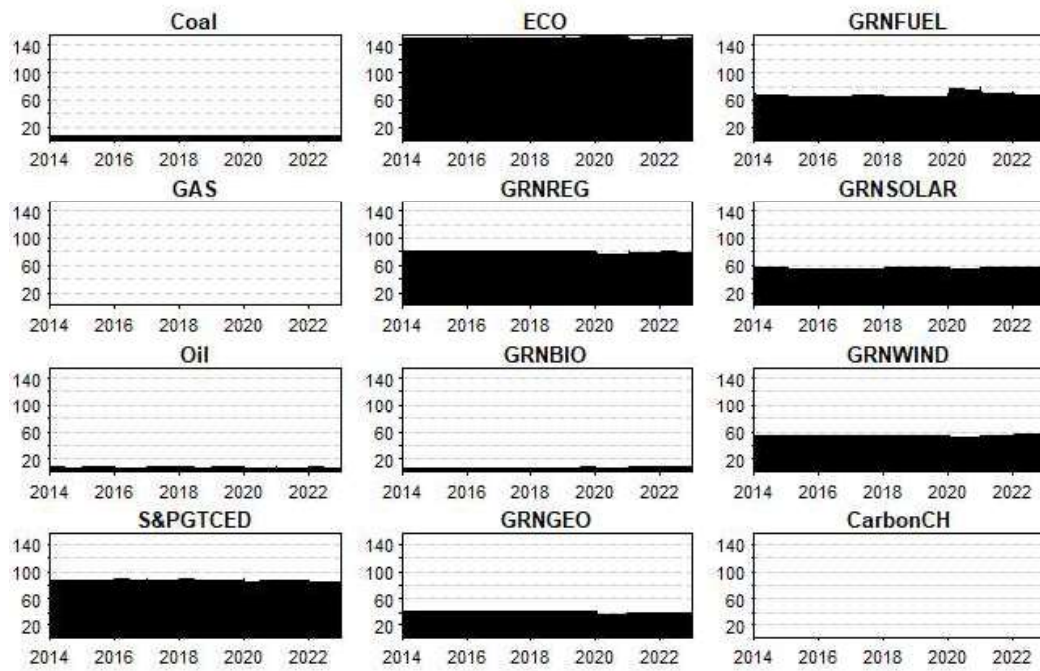


FIGURE 6.22 – Dynamic directional volatility connectedness TO others : China

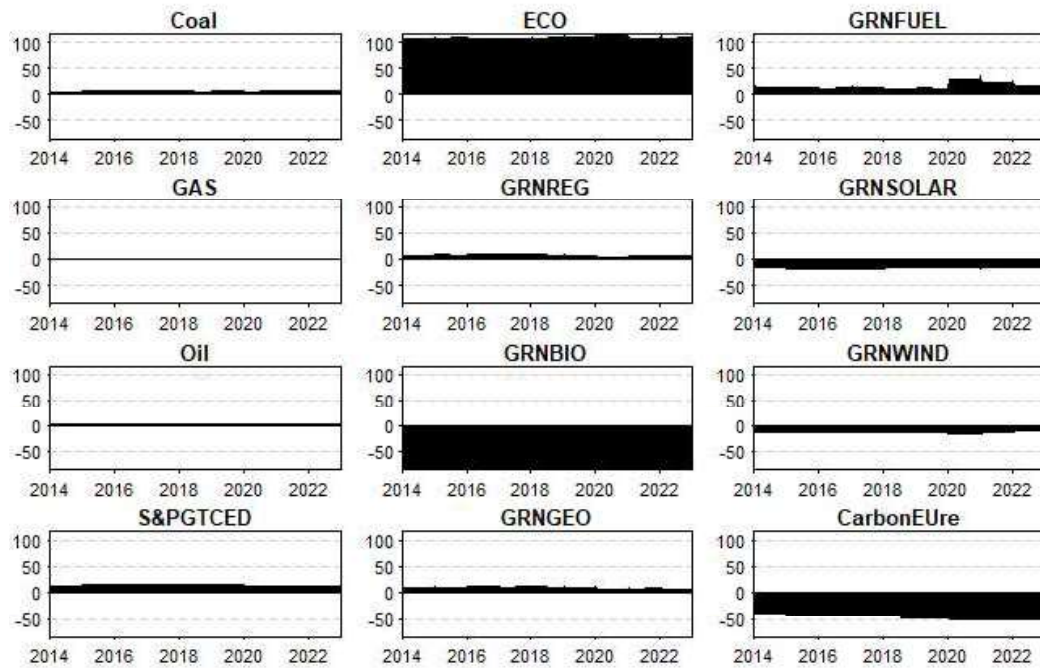


FIGURE 6.23 – Total net volatility connectedness : Europe

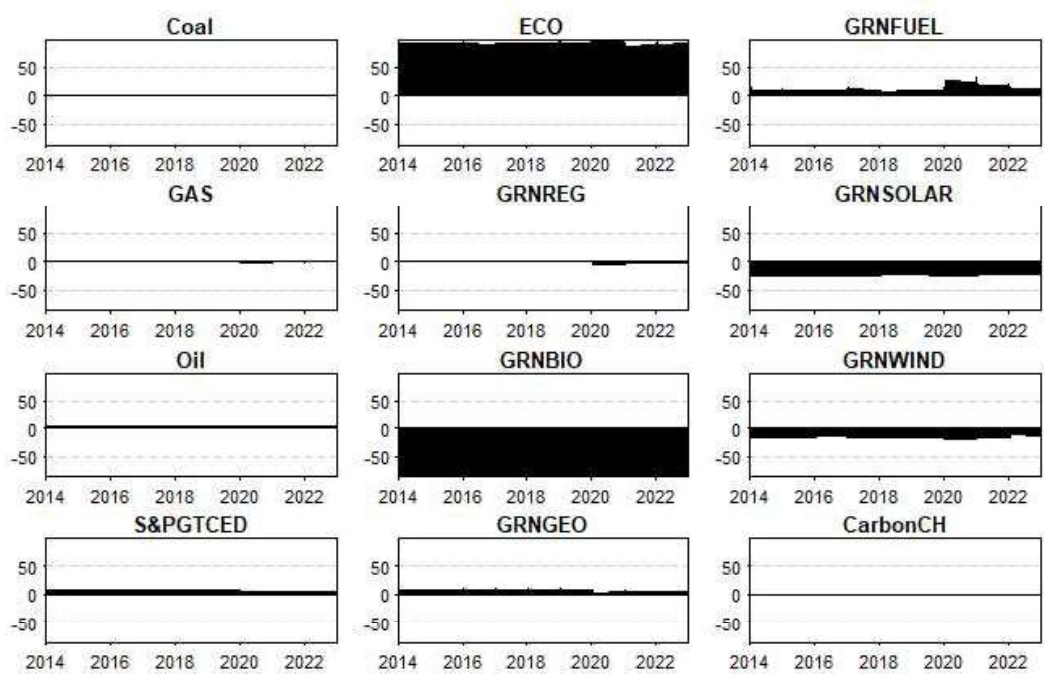


FIGURE 6.24 – Total net volatility connectedness : China

Chapitre 7

Conclusion

7.1 Main results

This thesis deals with the complex relationships between financial markets, energy sectors, the carbon market, and carbon emissions. The main objective is to study the influence of stock market activity and economic activities on environmental degradation and carbon market mechanisms from different perspectives. As highlighted by Wu and Jiang in 2023, the dynamic relationship between stock, energy, and carbon markets is not yet clear. Previous studies on the nexus between the stock market, energy, and carbon markets exhibit some limitations : (i) Limited focus : only a few studies have focused on the link between the stock market and carbon, paying particular attention to the asymmetrical impact of the stock market on the carbon. (ii) Limited analysis : Existing studies provide limited information on the impact of decomposed oil price shocks on the carbon market, particularly during global major events. (iii) Regional comparison : Another limitation is the lack of comparative analysis of the relationships between these markets under different market conditions, particularly in different regions.

Understanding the dynamic linkage between these markets is essential, as it is crucial for optimizing energy allocation, facilitating society's transition to low-carbon practices, and effectively managing risks. This thesis addresses the existing research gap concerning the relationship between the financial and economic spheres and carbon through four complementary research studies.

The first study highlighted the links between stock market development, energy efficiency, and environmental quality. The main objective of this study is to analyze the symmetric and asymmetric dynamic relationship between stock market development and carbon emissions in emerging market economies. A new contribution to the literature, this study examines the impact of positive and negative shocks in stock markets and energy efficiency on carbon emissions. This analysis uses the linear and non-linear panel ARDL model to examine the symmetric and asymmetric impact of stock market development and energy efficiency on carbon emissions in the short and long run. The findings of this study suggest that the symmetric effects of stock market development on carbon emissions

indicate that stock market development had negative environmental effects in emerging market economies, which is consistent with the findings of Paramati et al. (2017). However, the results of the non-linear estimation reveal a more complete view, indicating that both positive and negative shocks to stock market development can increase carbon emissions. First, The results of the linear model showed that, in the long term, the development of stock markets in emerging economies tends to increase carbon emissions. This is because the development of stock markets attracts funds to finance production and manufacturing activities, which often lead to increased energy consumption, particularly fossil fuels. This effect is more pronounced in countries with weak environmental regulations, leading to increased carbon emissions. Second, the results of the asymmetric model show that negative shocks have a greater impact than positive shocks on carbon emissions in emerging market economies. When stock markets are less developed, there will be a lack of funds available to finance the adoption of renewable energies. As a result, the consumption of fossil fuels increases in regions where environmental regulations are relatively weak, contributing to rising carbon emissions.

The second study examined the asymmetric links between equity, energy, and carbon markets in Europe and China. To achieve this, the study uses the asymmetric GARCH BEKK model to study the non-linear impacts and volatility transmission between stock, energy, and carbon markets and DCC GARCH (1,1) model to capture the changing correlation dynamics over time among the markets. The results of this study revealed significant findings concerning the interaction between stock markets, carbon markets, oil price, and green bond indices. It demonstrates a strong transmission of volatility between stock markets and carbon markets. The Chinese carbon market played a central role in the volatility transmission, establishing links between the stock market, oil prices, and the green bond index. However, European results indicate no direct link between oil prices and the green bond market. In addition, the relationships vary according to market integration and maturity degree, with Chinese markets showing shorter-term dynamics and European markets showing longer-term interactions. Moreover, We observed asymmetrical spillover effects in China, which positive news increases the volatility level in carbon and green bond markets. These results provide valuable information for investors and policy-makers, underlining the need for a dynamic approach and knowledge transfer from mature markets to foster sustainable economic growth.

The third study investigated how European and Chinese carbon markets respond to oil price shocks. According to Killian 2009, the effect of oil shocks on the economy and finances may depend on the source of the shock. When oil prices rise due to supply factors, the result can be high production costs for companies, which is detrimental to their business. Conversely, an oil demand shock positively correlates with the global economy, helping to create favorable market conditions. Furthermore, oil shocks are closely linked to the health of global financial markets, with a high oil shock indicating an unstable financial environment. It is, therefore, essential to analyze how these oil shocks impact carbon market returns. We used a method of decomposing the oil price into Ready 2018 supply, demand, and specific risk shocks. We used a structural vector autoregression (SVAR) model to analyze the impact of these shocks on carbon markets. To improve our analysis, we refined the model using a structural vector autoregression

with time-varying stochastic volatility (TVP-SVAR-SV) to capture the evolving relationships between these variables. Our results revealed distinct responses of carbon markets in Europe and China to oil supply, demand, and risk shocks. In Europe, the response to oil supply and demand shocks was consistently positive, while the response to risk-related shocks was negative, underlining the market's stability and investment potential. In contrast, China's carbon market reacted much more positively to oil demand shocks, reflecting its dependence on oil and the strength of its industrial sector. However, it proved more sensitive to oil-related financial shocks, particularly during the 2014 oil crisis, due to the relative newness of its carbon market and its limited regulatory framework.

The last study examined the interconnectedness between the European and Chinese carbon markets, three key fossil fuels, and eight global clean energy indices. This study investigated the complex interplay between the carbon markets of two regions, fossil fuels, and major clean energy indices. It used advanced methodologies, including TVP-VAR and DCC-GARCH combined with the Diebold and Yilmaz 2012 connectivity model, to quantify return and volatility transmissions, offering a nuanced understanding of the dynamics of these markets. The results showed that in Europe, the renewable and clean energy markets played a unique role in influencing European carbon market returns, while fossil fuels were not directly linked to carbon market. The Chinese carbon market presented a more complex network of influences, including clean energy and fossil fuel domains. Furthermore, regarding volatility spillover, the European carbon market received volatility from clean energy indices, indicating relative isolation from fossil fuel market volatility. In contrast, the Chinese carbon market also showed minor spillover effects, underlining the need for targeted strategies to balance and sustain the energy landscape.

7.2 Policy implications

The implications of our thesis are of considerable importance to a range of stakeholders, including policymakers, investors and corporate managers. The results provide new insights that can inform decision-making and shape actions in the following ways :

7.2.1 For policymakers :

Our research provides valuable insights for policymakers, highlighting the importance of understanding the fundamental variables influencing environmental quality and the carbon market mechanism. By understanding these variables, governments and policymakers can design sustainable development plans and effectively address environmental challenges. Through our studies, we have formulated recommendations for regulators concerning environmentally friendly policies, regulatory aspects, and the monitoring and evaluation of the effectiveness of these regulations.

Regarding environmentally friendly policies, in emerging market economies, where the development of stock

markets can have a negative impact on the quality of the environment, regulators should give priority to environmentally friendly policies. These policies should promote the transition to green technologies and renewable energy sources while enforcing stricter emissions regulations.

Concerning regulatory frameworks, it is essential to establish clear and coherent regulatory frameworks regulating interactions between the carbon, renewable energy and fossil fuel sectors. Such clarity fosters transparency, predictability, and an environment conducive to cross-sector collaboration and sustainable growth.

Finally, for monitoring and evaluation, ongoing monitoring, evaluation, and research are essential, particularly in relatively immature markets. Regulators must adapt policies to changing market dynamics and ensure policies align with the evolving energy landscape.

7.2.2 For investors :

Our findings shed light on risk management through diversification, long-term perspectives and monitoring of regulatory developments. With regard to portfolio diversification and risk management, investors should diversify their portfolios to mitigate the risks associated with the interconnection between carbon, equity and energy markets. Investors should diversify their portfolios to spread risk and mitigate the potential negative impacts of interconnectedness between carbon, equity, and energy markets. By allocating investments across different asset classes or markets, they can reduce vulnerability to specific market shocks and enhance overall portfolio resilience. Diversification helps manage volatility, adapt to changing market conditions, and maintain a long-term perspective, making it a key strategy for effective risk management in a complex and interconnected financial landscape.

In addition, taking into account the asymmetrical impacts of shocks is crucial, and risk management strategies must be able to adapt to changing market conditions. As for the long-term outlook, in both Europe and China, investors should adopt a long-term perspective, taking into account the unique characteristics of each region's markets. Sustainable investments aligned with environmental commitments can produce favorable returns over time. To monitor regulatory developments, investors should keep a close eye on regulatory developments in the carbon, clean energy, and fossil fuel sectors, as these can have a significant impact on market dynamics. Keeping abreast of policy changes and their potential effects is essential to making informed investment decisions.

7.2.3 For corporate managers :

Through our thesis, we provide valuable advice to business leaders on how to address environmental challenges and improve their carbon efficiency. Firstly, we highlight the importance of environmental innovation, encouraging business leaders to prioritize investments in green technologies and sustainable practices. These initiatives, such as the adoption of renewable energies and the decarbonization of production processes, are effective measures for mitigating environmental impacts and aligning with sustainability goals. In addition, our research highlights the

importance of integrating a robust risk management framework. Business leaders need to understand the complex links between carbon, equity, and energy markets to make appropriate decisions. This comprehensive understanding enables them to anticipate and assess potential market shocks and their environmental implications, enabling proactive risk mitigation.

In addition, we emphasize the essential role of environmental compliance, particularly in regions where the development of stock markets can have a negative impact on environmental quality. Business leaders should prioritize strict compliance with emissions regulations to mitigate negative environmental impacts and encourage responsible business practices. Moreover, our thesis highlights the need for adaptive strategies, particularly in markets where positive stock market shocks can increase emissions and negative shocks can constrain investment in green technologies. Business leaders should develop and proactively implement strategies that balance financial growth with environmental responsibility, enabling them to navigate uncertain economic conditions while maintaining their commitment to environmental sustainability.

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