Essays on Carbon Pricing and Carbon Markets

Thesis submitted to the Université de Lille, France and Université Catholique de Louvain, Belgium
Doctor of Philosophy in Economics Sciences

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Essais sur la tarification et les marchés du carbone

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Doctorat en sciences économiques

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Sous la direction de

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Declaration

I, Karishma ANSARAM KOOSHNA, declare that this thesis, entitled 'Essays on Carbon Pricing and Carbon Markets' and the work presented in it are my own. I confirm that:

- This work was done wholly or mainly while in candidature for a research degree at the two universities.
- Where I have consulted the published work of others, this is always clearly attributed.
- Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work.
- I have acknowledged all main sources of help.
- Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself.
- **Authors' Contribution**: Chapter Two and Three has been co-authored with Dr Paolo Mazza, HDR from IESEG School of Management. The latter has contributed in reviewing the papers mainly. Chapter Four has been co-authored with Dr Paolo Mazza, HDR and Dr Zakriya Mohammed from IESEG School of Management. Both have contributed in reviewing the methodology and the paper overall. Chapter 5 has been co-authored with Dr Mikael Petitjean from UC Louvain. He contributed in identifying the research question and methodology, strengthening the conceptual framework and reviewed the paper.

K.Ansaram

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Summary

Economists see climate change as a market failure that imposes huge costs and risks on future generations, who will suffer the consequences of climate change. These costs are not being reflected in current market prices. In order to internalise these costs, the notion of carbon pricing has a vital role to play. Globally, the adoption of carbon pricing is growing exponentially, but the big questions governing this trend remain unanswered. The thesis aims at addressing the gaps and providing insights on the ongoing debates on carbon pricing from different angles.

The study answers four main ongoing discussions on carbon pricing globally. It addresses the following gaps: 1) the convergence and dependence of carbon markets globally; 2) the influence of stakeholders through news announcements on carbon prices; 3) the efficiency of adopting single or multiple carbon pricing and 4) the presence of renewable energy coupled with technology and carbon prices to influence stock prices.

The first paper reviews the dependence structure between eight carbon markets globally through different copulas for the period 2011-2019. The objective is to see convergence towards a global carbon market. The results demonstrate an asymmetric relationship between most carbon markets but a higher tail dependence between carbon markets that have linkage agreements, ongoing cooperation, or are geographically close.

The second paper looks into the impact of news announcements on carbon prices across eight carbon markets by defining seven categories of the news from Bloomberg for the period January 2015 to June 2020. The results showcase that news announcements have an impact on carbon prices, and the magnitude of the market reaction is a function of the type of news. Positive news seems to have a longer effect than negative news. Similarly, the news' categories tend to influence the carbon markets differently. Carbon markets react more to market reforms than to other announcements such as controversies, lobbying, or the Paris Agreement.

The third paper investigates the race for carbon pricing amongst firms i.e., the adoption of single or multiple carbon pricing mechanisms (carbon trading, carbon tax, and/or internal carbon price) on the environmental performance of 2,303 firms. The results show that while carbon taxes can independently provide significant improvements in environmental performance, carbon trading and internal carbon pricing are ineffective on their own, and can even be detrimental in some cases. There are significant heterogeneities in the effectiveness of CPMs in carbon-intensive sectors versus other sectors and in different regions.

The fourth paper showcases the presence of renewable energy in a carbon pricing world and how it impacts on stock prices through the Divisia Index. The paper retrieves data for both the price and consumption of fossil energy (oil, coal, and gas) *and* renewable energy (solar, wind, and hydro). A Vector Autoregressive (VAR) model has been estimated over the period 2000-2019 across 25 countries globally. The study identifies significant time-dependent dynamics between renewable energy and both the energy stock and carbon markets, while fossil energy has no significant influence on those markets.

Résumé

Les économistes considèrent le changement climatique comme une défaillance du marché qui impose des coûts et des risques énormes aux générations futures qui subiront les conséquences du changement climatique. Ces coûts ne sont pas reflétés dans les prix actuels du marché. Afin d'internaliser ces coûts, la notion de tarification du carbone a un rôle essentiel à jouer. À l'échelle mondiale, l'adoption de la tarification du carbone connaît une croissance exponentielle, mais les grandes questions régissant cette tendance restent sans réponse. La thèse vise à combler les lacunes et à donner un aperçu des débats en cours sur la tarification du carbone à partir de différents volets.

L'étude répond à quatre principales discussions en cours sur la tarification du carbone à l'échelle mondiale. Il comble les lacunes suivantes ; 1) la convergence et la dépendance des marchés du carbone à l'échelle mondiale, 2) l'influence des parties prenantes par le biais d'annonces sur la tarification du carbone, 3) l'efficacité de l'adoption d'une tarification unique ou multiple du carbone et 4) la présence d'énergies renouvelables associée à la technologie et au prix du carbone pour influencer les cours des actions.

Le premier article examine la structure de dépendance entre huit marchés du carbone dans le monde à travers différentes copules pour la période 2011-2019. L'objectif est de voir la convergence vers un marché mondial du carbone. Les résultats démontrent une relation asymétrique entre la plupart des marchés

du carbone, mais une dépendance extrême plus élevée entre les marchés du carbone qui ont un accord de liaison, une coopération en cours ou qui sont géographiquement proches.

Le deuxième article examine l'impact des annonces sur les prix du carbone sur huit marchés du carbone en définissant sept catégories d'informations de Bloomberg pour la période de janvier 2015 à juin 2020. Les résultats montrent que les annonces ont un impact sur les prix du carbone et l'ampleur de la réaction du marché est fonction du type de nouvelles. Les nouvelles positives semblent avoir un effet plus long que les nouvelles négatives. De même, les catégories d'informations ont tendance à influencer différemment les marchés du carbone. Les marchés du carbone réagissent plus aux réformes du marché qu'à d'autres annonces telles que les controverses, le lobbying ou l'Accord de Paris.

Le troisième article étudie la course à la tarification du carbone parmi les entreprises, c'est-à-dire l'adoption de mécanismes de tarification du carbone uniques ou multiples (échange de carbone, taxe sur le carbone et/ou prix interne du carbone) sur la performance environnementale de 2 303 entreprises. Les résultats montrent que si la taxe sur le carbone peut indépendamment apportent des améliorations significatives aux performances environnementales, le commerce du carbone et la tarification interne du carbone sont inefficaces en eux-mêmes et peuvent même être préjudiciables dans certains cas. Il existe d'importantes hétérogénéités dans l'efficacité des CPM pour les secteurs à forte intensité de carbone par rapport à d'autres secteurs et dans différentes régions.

Le quatrième article présente la présence des énergies renouvelables dans un monde où le prix du carbone est élevé et son impact sur les cours des actions via l'indice Divisia. Le document récupère des données à la fois sur le prix et la consommation d'énergie fossile (pétrole, charbon et gaz) *et* d'énergie re-

nouvelable (solaire, éolienne et hydraulique). Un modèle vectoriel autorégressif (VAR) a été estimé sur la période 2000-2019 dans 25 pays du monde. L'étude identifie une dynamique temporelle significative entre les énergies renouvelables et les stocks d'énergie et les marchés du carbone, tandis que les énergies fossiles n'ont pas d'influence significative sur ces marchés.

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Abbreviations

CDM	Clean Development Mechanism
CER	Certified Emission Reduction
COP	Conference of Parties
CPM	Carbon Pricing Mechanism
DID	Differences in Differences
EEX	European Energy Exchange
ESM	Event Study Methodology
ETS	Emissions Trading System
EU	European Union
EUA	European Union Allowance
GHG	Greenhouse Gas
ICP	Internal Carbon Pricing
IEA	International Energy Agency
IMF	International Monetary Fund
IPCC	Intergovernmental Panel on Climate Change
NAP	National Adaptation Plan
NCT	Natural Capital Theory
NDC	Nationally Determined Contribution
NYMEX	New York Mercantile Exchange
PSM	Propensity Score Matching
OECD	Organisation for Economic Cooperation and Development
RGGI	Regional Greenhouse Gas Initiative
VAR	Vector Autoregressive
VD	Variance Decomposition
WTO	World Trade Organisation

Chapter 1

General Introduction

The Intergovernmental Panel on Climate Change (IPCC), as the most comprehensive assessment of climate change, affirms that it is likely that human influence has been the dominant cause of observed warming since the mid-20th century (IPCC, 2021). There is a call for global cooperation to mitigate this human-induced climate change by at least 3 degrees Celsius on average compared to the pre-industrial era (Stavins et al., 2014). However, this problem is coupled with uncertainty between the physical impact of climate change and the magnitude of the social cost of Greenhouse Gases (GHG) (Masson-Delmotte et al., 2022). Climate change has been labelled as an environmental externality that encompasses complex causes that are dispersed by timing, geography, and magnitude (Nordhaus, 1991; Stern and Stern, 2007). In 1920, economist Arthur Cecil Pigou put forward a tax to protect environmental goods (Pigou, 1924). The latter's intuition rests on the argument that polluting the environment should not be cost-less. If pollution is costly, then it creates an incentive to avoid or reduce polluting activities (Mintz-Woo, 2022). Establishing a successful carbon price equal to the full climate change-related external costs will help to equalize the marginal social and private costs of GHG emitting activities

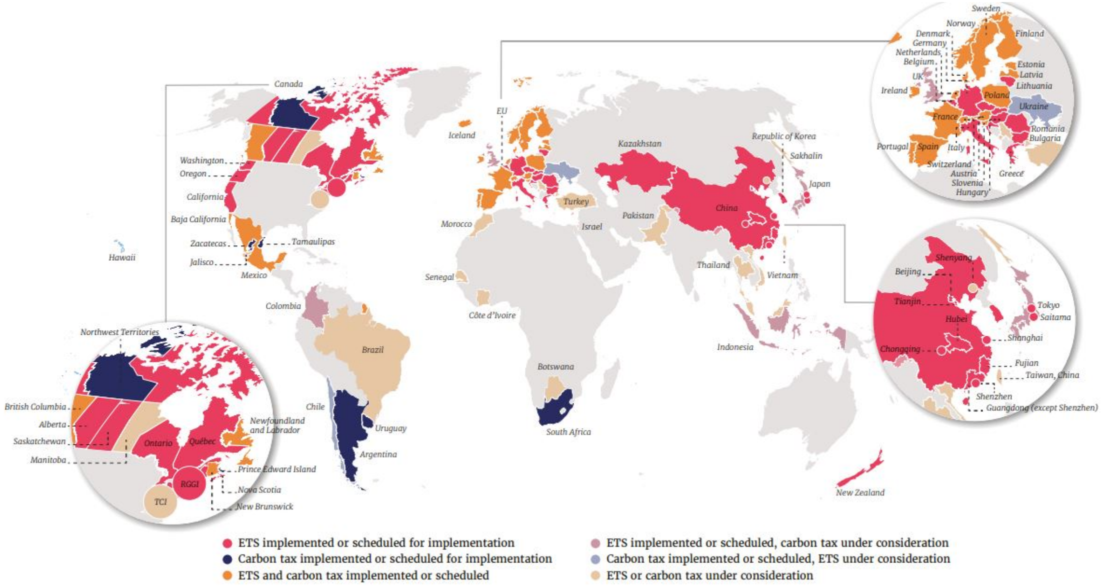
(Weisbach and Metcalf, 2009). A recent systematic review of the literature on carbon pricing by Khan and Johansson (2022) stipulates that carbon pricing internalises the costs amongst households and companies, ultimately affecting production and purchasing behaviour.

Additional political economy constraints gave rise to different theories. Eisenhardt (1989) portrays climate change as a principal-agent problem whereby the principal agents face a higher share of mitigation costs than benefits, while the huge number of actors required to take simultaneous action to reduce emissions introduces all kinds of collective action challenges, including strong incentives for free ridership. Other examples include, the 'polluter pays principle' which is considered to overcome the challenge of free-riding, whereby each player should internalize the negative externalities of their CO_2 emissions. The private costs of climate mitigation should be felt in the near term and assume an equitable distribution of mitigation responsibilities in industrialized nations.

As the threats of this global phenomenon become more acute and visible, climate change is now a key priority for policymakers around the world. The international political arena on climate change has known several pitfalls and successes through the journey of accords and agreements related to carbon pricing. The Kyoto Protocol was ratified in 2005 by thirty-seven industrialised nations to stabilise GHG emissions. The protocol weighs more on the industrialised nations known as Annex I countries to reduce six main GHG emissions by a minimum of 5% between 2008 and 2012 (Arouri et al., 2012). Kyoto Protocol harboured the Clean Development Mechanism (CDM) and Joint Implementation. The latest and ongoing agreement from COP21, the Paris Agreement at COP 21 was deemed a diplomatic success compared to the Copenhagen Accord in 2009 (Boroumand et al., 2022). Each country under the Paris Agreement is expected to ratify their nationally determined contributions (NDCs) to reduce CO_2 emissions through a formalised stocktaking process. So far, 59 parties to the Paris Agreement, accounting for 54 percent of global emissions have committed to net-zero emissions by mid-century. Making sufficient progress to stabilise the climate requires ratcheting up near-term mitigation action, but doing so within an era of debates on pricing externalities is challenging. Article 6 of the Paris Agreement has emerged as a new anchor for carbon trading. Under its aegis, Article 6.4 sets the base for a sustainable development mechanism under international oversight, and Article 6.2 unlocks the transfer of international mitigation outcomes between two states or via clubs. The modalities of Article 6 are still under development and the carbon trading mechanisms are under much debate.

While there is increasing ambition to implement climate policies, studies show that countries will still fail to meet the climate targets. The current state of carbon pricing is experiencing gaps between policies and pledges such as NDCs and net zero (World-Bank, 2021). Thus, understanding the notion of carbon pricing and leveraging its characteristic is crucial to closing this policy gap while addressing social and environmental concerns.

Carbon pricing can be grouped into two instruments at the macro level; carbon taxes and emission trading systems (ETS). A carbon tax is a policy instrument through which the government levies a fee on GHG emissions, providing a financial incentive to lower emissions. The price or rate is set by the government. On the other hand, an ETS involves placing a limit or cap on the total volume of GHG emissions in one or more sectors of the economy. Regulators can auction or distribute the tradable emission allowances to entities covered by the system. Covered entities are required to submit their allowances for their emissions during a compliance period. They can choose to buy additional allowances if necessary or sell surplus allowances. In an ETS, the price of carbon is governed by the demand and supply of emission allowances or credits.



Carbon pricing initiatives are considered "scheduled for implementation" once they have been formally adopted through legislation and have an official, planned start date. Carbon pricing initiatives are considered "under consideration" if the government has announced its intention to work towards the implementation of a carbon pricing initiative and this has been formally confirmed by official government sources. TCI refers to Transportation and Climate Initiative. RGGI refers to the Regional Greenhouse Gas Initiative.

Figure 1.1: Map of carbon taxes and ETSs
Source (World-Bank, 2021)

The adoption of carbon pricing policies has been largely concentrated in high and middle-income countries. As of April 2022, there are 68 carbon pricing policies in operation, with three more scheduled for implementation. This comprises of 37 carbon taxes and 34 ETSs (see figure 1.1. Carbon pricing systems, such as cap-and-trade, can exist at regional (e.g., European ETS), national (e.g., Chinese ETS), or sub-national (e.g., Californian) levels. So far, China hosts the world's largest carbon market by emissions and the EU ETS hosts the largest carbon market by traded value, whereby prices are both in spot and future contracts.

Carbon pricing policies are also subject to debate and controversy. Despite the surge in carbon pricing policies, the prices in most jurisdictions are lower than what is needed to meet the goals of the Paris Agreement (World-Bank, 2021). Stiglitz et al. (2017) authored a High-Level commissioned report on carbon prices, recognising that 'a well-designed carbon price is an indispensable part of a strategy for reducing emissions in an efficient way'. The report supports explicit price trajectories rather than one single price for carbon in all places. d'Autume et al. (2016) argue that a uniform carbon price will be ineffective without international transfers between governments. The implicit carbon prices are highly divergent from close to zero to well above 100 USDtCO_2, according to Aldy et al. (2016), giving rise to a considerably higher global cost of emissions abatement than necessary. In 2021, the International Monetary Fund (IMF), the Organisation for Economic Co-operation and Development (OECD), and the World Trade Organisation (WTO) favoured the idea of a global price on carbon emissions. The latter argues that in a WTO-compliant environment, a single price will curb carbon leakage. Further, given that the current mitigation pathway to attain the Paris Agreement goal is well below 2-degree, the adoption of a single rate is preferable (Wood, 2018). The IMF even proposed an international carbon price floor, taking into consideration countries' development levels. Some countries are looking into cross-border policies and initiatives that can enable higher carbon prices. Opening trading to other financial players can lead to more liquidity in the market.

Another school of literature supports the idea that carbon pricing cannot solve climate change alone. It needs to be coupled with other sustainable policies (Meckling, 2011). For example, Patt and Lilliestam (2018) argues that carbon pricing brings along transition frameworks that need to stimulate low carbon technologies. In order to avoid the risk of exceeding the 1.5-2 degree threshold, it requires emissions to fall to net zero by mid-century. Under such conditions, carbon pricing cannot be the sole driver of emission reductions. Metaphorically, there is a need to address all energy production across all sectors and firms, drowning out the importance of heterogeneous mitigation costs. This brings along the role of firms and their adoption of carbon pricing mechanisms. World-Bank (2021) reports a growth in the implementation of internal carbon pricing in the private sector. Firms put a price on the CO_{2e} emitted by their activities (Bartlett et al., 2017). Trinks et al. (2022) and Wang (2013) call for further investigation of firms' carbon-reduction targets and call for a further analysis of concrete firm carbon-reduction activities and their determinants.

The thesis aims at addressing the gaps and providing insights on the ongoing debates on carbon pricing from different angles. The economics of climate change have been extensively studied in recent decades. Although a consensus seems to have been reached on the necessity of pricing carbon, the most appropriate mechanism is still being debated. The study answers four main ongoing discussions on carbon pricing globally. It addresses the following gaps: 1) the convergence and dependence of carbon markets globally; 2) the influence of stakeholders through news announcements on carbon pricing; 3) the efficiency of adopting single or multiple carbon prices and 4) the presence of renewable energy coupled with technology and carbon price to influence stock prices.

The climate finance community needs a holistic view on carbon pricing, and this is what the study aims to provide. The key contribution lies in the assessment of carbon pricing both at the macro level in Chapters 2 and 3 and at the micro level in Chapters 4 and 5. Only a handful of studies have looked into multiple carbon markets simultaneously or even looked at the three types of carbon pricing mechanisms in a single study. Additionally, it extends to appraise the presence of diverse stakeholders and policies that influence carbon pricing as advocated by Raymond (2019). Stakeholders such as lobbyists, policymakers, firms, and carbon traders have been considered. Policies such as decarbonization and adoption of renewable energy strategies, technological innovation, and board governance have been investigated. Given the diversity of the study, different audiences can benefit from the results, ranging from policymakers setting national and international regulations to carbon market players, firms adopting carbon pricing, and activists advocating for effective carbon pricing.

In line with the recommendations to either have a single carbon price or form market clubs, the first axis of the study looks into the global environment of carbon markets by measuring the dependence structure among carbon markets (Stiglitz et al., 2017; d'Autume et al., 2016). The dependence between eight carbon markets has been appraised, and it has policy implications for setting international frameworks for carbon trading, ensuring liquidity, maintaining an effective price level of carbon, and avoiding carbon leakage. However, the market structure is not the sole driver of carbon prices. In order to have a holistic view of how different stakeholders can impact carbon prices, a second study has been introduced.

The second strand of this study looks into how those eight carbon markets are impacted by news announcements. It goes beyond the study of policy or market reforms by incorporating news from various stakeholders, such as lobbyists (Song et al., 2018; Hintermann, 2010; Mansanet-Bataller and Pardo, 2009; Mckenzie et al., 2004). Seven categories of news have been defined from Bloomberg's news section on carbon markets. The results strengthen the arguments that the notion of carbon pricing goes beyond the technical aspects and should consider the community and stakeholders as well. While the first two studies are focused on carbon markets, the presence of other types of carbon pricing mechanisms (CPMs) cannot be ignored. It is crucial to appraise how different CPMs perform individually and when paired.

The third aspect of carbon pricing is related to its efficiency in reducing emissions. There is sporadic adoption of carbon pricing in the form of carbon trading, carbon taxes and internal carbon prices globally. However, the literature has been constrained to study the impact of either one or a comparison of two carbon prices simultaneously (Damert and Baumgartner, 2018; Gouldson and Sullivan, 2013; Hoffman, 2005; Lee, 2012). This study goes beyond and investigates the adoption of the three forms of carbon pricing mechanisms by firms and their influence on environmental performance measured through energy intensity, carbon intensity, and environmental score. Nevertheless, the impact of carbon pricing should be expanded to other variables. CPMs can also have a causal relationship with other factors such as innovation, renewable energy, and financial stocks. In an attempt to study the role of carbon pricing in influencing stock prices in a world led by energy prices, the fourth paper has emerged.

The fourth strand lies in the controversy about carbon pricing and long term decarbonization. Research suggests that a renewable energy portfolio might help build an ambitious carbon pricing (Meckling et al., 2017). There is limited reference to how the presence of renewable energy prices and carbon pricing can influence stock prices. The fourth study thus investigates the influence of renewable energy and carbon prices on stock prices across 25 countries for the period 2000-2019.

The summary of chapters provides further details on the main research question, methodology, use of data, and key outcomes from each axis that has been investigated.

Summary of Chapters

Chapter 2: Dependence Structure Among Carbon Markets Around the World: New Evidence from GARCH-Copula Analysis

Since the introduction of emission trading systems in 2005, several studies have analysed the co-integration of carbon prices from diverse angles: In the same market (for example Chevallier et al. (2010), Trück et al. (2014) and Wu and Hu (2014) for integration between spot and future carbon prices as well as

Zhu et al. (2020a) for the Chinese pilot carbon market's risk of spillovers), co-integration between two carbon markets and/or between one carbon market and other energy markets (For example Kanamura (2016), Cherubini et al. (2011) and Zeng et al. (2021) for co-integration between the European carbon market and Certified Emission Reductions (CERs), Chun (2018) for spillovers between the European and Chinese carbon markets and Balcılar et al. (2016) for cross market correlations between the European carbon market and other energy markets). Establishing the stochastic relationships intertwined in carbon markets remains a challenging task. This chapter investigates the dependence structure among carbon markets globally through different copulas. The analysis explores the relationship between carbon prices being traded across different ETS worldwide. The novelty rests in assessing carbon allowances for both futures and spot prices across all the key carbon markets, such as the EU, RGGI, California, Quebec, and South Korea, as well as the three Chinese carbon markets, Shenzhen, Guangdong, and Hubei, for the period 2011 to 2019 for future prices and 2015 to 2020 for spot prices. The results demonstrate an asymmetric relationship between most carbon markets. A low tail dependence has been noted between the EU and RGGI, California, and Quebec carbon markets, while higher a tail dependence has been registered with the Asian carbon markets. Further, carbon markets that have linkage agreements, ongoing cooperation, or are geographically close tend to have positive and higher tail dependence. The paper points out that regional carbon clubs are being formed as per the dependence structure.

Chapter 3: Simultaneous Impact of News Announcements on Global Carbon Prices

Carbon markets play a crucial role in global energy markets and towards climate goals. The adoption of climate policies will bear on the competitiveness, productivity, and the pricing of carbon emission permits, which have drawn the attention of academic research. Understanding how international climate-related news shapes the price dynamics in this market is important for market participants and has been chronically studied. For example, Miclaus et al. (2008); Mansanet-Bataller and Pardo (2009); Lepone et al. (2011); Chevallier et al. (2009) investigated the impact of news announcements in EU ETS and found a significant time-varying impact on carbon prices. Compared to existing studies that focus on a single category of news from market-based regulations, this paper contributes to the literature by investigating to what extent announcements from diverse stakeholders can impact the carbon prices. We examine the effect of seven news categories (controversies and uncertainty, lobbying by stakeholders, linkage of carbon markets, carbon market reforms, policy makers' ambition, new carbon markets, and Paris Agreement news) encompassing international announcements on prices in eight carbon markets around the world by running an event study on daily stock returns for spot contracts from 20 January 2015 to 30 June 2020. Using news derived from Bloomberg's carbon markets news section and an event study methodology, our results show that news announcements have an impact on carbon prices, and reactions' magnitude differs depending on the type of news. Positive news seems to have a longer effect than negative news. Similarly, the categories of news tend to influence the carbon markets differently. Market reforms significantly impact the carbon markets as compared to other third-party announcements, such as controversies and lobbying. The oldest ETSs, i.e., EU and RGGI, are more impacted by the announcements than the latest ones. Finally, announcements tend to have an immediate impact on carbon markets rather than a post-event effect or an anticipation of such news.

Chapter 4: The Race for Carbon Pricing Amongst Firms

Firms bear the additional costs that ultimately reduce their profitability if they are not environmentally conscious (Rezaee et al., 2017) and are concerned about carbon pricing regulations negatively impacting their profitability (Fu et al., 2023). In this study, we analyse multiple CPMs within a single framework: carbon trading on compliance markets, carbon taxes, and internal carbon pricing. The aim is to understand how multiple carbon pricing mechanisms, i.e., carbon market trading, carbon tax, and internal carbon pricing, impact the firms' environmental performance. To be more precise, this paper contributes to the literature by addressing the following questions: Do carbon pricing mechanisms effectively impact environmental performance? Does the adoption of multiple carbon pricing mechanisms amplify their impact on environmental performance? Using horse race regressions on a sample of 2,303 firms, we capture the relative impact of the presence of single *and* multiple CPMs on firms' environmental performance measured through carbon intensity, energy intensity, and environmental score. The results indicate that the presence of a carbon pricing mechanism significantly improves carbon intensity and the environmental score. Further analysis shows that carbon tax is the only mechanism that can improve environmental performance on its own; carbon trading and internal carbon prices should be paired in order to be significant. Surprisingly, the presence of all three types of carbon pricing mechanisms does not influence environmental performance. The results also indicate that carbon pricing mechanisms adopted by highly carbon-intensive firms are more likely to reduce emissions and improve environmental performance. The role of environmental innovation and board members' independence as moderating variables has been uncovered. The presence of multiple carbon pricing mechanisms requires a high rate of environmental innovation and strong board independence to improve the environmental performance.

Chapter 5: A Global Perspective on the Nexus Between Energy and Stock Markets in Light of the Rise of Renewable Energy

The rise in renewable energy and the associated divestment initiatives from fossil fuels around the world have become prominent in combating climate change. As pointed out by Gallego-Álvarez et al. (2015), the transition to low carbon can have a positive effect on financial performance because investors can better select the optimal investment portfolio to reduce their risks and get excess returns. For example, abrupt volatility and correlation changes in renewable and fossil energy prices can hit energy intensive companies heavily, and investors have an incentive to identify the better-positioned companies that can quickly adjust their level of energy consumption and adopt innovative technologies (Gong et al., 2021). This paper revisits the relationship between energy and stock markets by accounting for renewable energy through the use of the Divisia index method. The paper contributes to the literature by using three renewable energy tariffs rather than relying on clean energy stocks as a proxy for renewable energy. We retrieve data for both the price and consumption of fossil energy (oil, coal, and gas) *and* renewable energy (solar, wind, and hydro). We estimate a Vector Autoregressive (VAR) model over the period 2000-2019 across 25 countries globally. The study indicates that renewable energy is decoupled from fossil energy and has an insignificant relationship with the latter. In spite of (or because) of this decoupling, renewable energy is found to pave its own way to financial markets, especially through energy intensive companies. The risk of stranded assets and increasing divestment campaigns coupled with carbon pricing mechanisms incentivise companies to adopt a low carbon transition. The latter significantly influences carbon prices, i.e., increasing investment in renewable energy leads to a decrease in demand and an increase in supply for CO2 permits, further decreasing carbon prices. On the other hand, fossil energy exhibits no significant relationship with any of the variables tested. Our results also show that stock markets are not influenced by renewable energy or fossil energy but are significantly impacted by technology stocks and carbon prices.

Chapter 2

Dependence Structure of Carbon Markets

Article title: Dependence Structure Among Carbon Markets Around the World: New Evidence from GARCH-Copula Analysis

Abstract: In this paper, we investigate the dependence structure among carbon markets globally through different copulas. The novelty of our approach lies in assessing carbon allowances for both futures and spot prices across all the key carbon markets as well as the three Chinese carbon markets for the period from 2011 to 2019 for future prices and the period from 2015 to 2020 for spot prices. The results demonstrate an asymmetric relationship between most carbon markets. A low tail dependence was observed between the European Union ETS and Regional Greenhouse Gas Initiative ETS, California and Quebec carbon markets, while higher tail dependence was found in the Asian carbon markets. Furthermore, carbon markets that have linkage agreements, ongoing cooperation or are geographically close tend to have positive and higher tail dependence. Our findings suggest the formation of regional carbon clubs based on the dependence structure.

Keywords: Carbon markets, Carbon pricing, Copula models, Dependence structure

JEL: K00, K22, G14, G18, C12, C15.

2.1 Introduction

In the Paris Agreement, countries have pledged to reduce their carbon emissions to limit the global mean temperature increase to well below 2 degrees (Rogelj et al., 2017). The emission trading system (ETS), commonly known as the carbon market, is considered a pivotal tool for monitoring the commitments by the parties that ratified the agreement (Sousa et al., 2014). Since 2005, carbon markets have been mushrooming around the world (Michaelowa et al., 2019), and to date, there are 31 carbon markets that are currently in place or have been planned (Ramstein et al., 2020). Through carbon markets, the right to emit a given amount of CO2 becomes a tradable commodity and is a factor of production that is subject to stochastic price changes. Since the advent of emission trading systems in 2005, several studies have analyzed the behavior of emission allowance prices. A segment of this vast literature focuses on cointegration in the same market (for example, Chevallier et al. (2010), Trück et al. (2014) and Wu and Hu (2014) for integration between spot and future carbon prices as well as Zhu et al. (2020a) for the Chinese pilot carbon market's risk of spillovers). Another set of literature focuses on cointegration between two carbon markets and/or between one carbon market and other energy markets. The following are examples: Kanamura (2016), Cherubini et al. (2011) and Zeng et al. (2021) for cointegration between the European carbon market and Certified Emission Reductions (CERs), Chun (2018) for spillovers between the European and Chinese carbon markets, and Balcılar et al. (2016) for cross-market correlations between the European carbon market and other energy markets. Establishing the stochastic relationships between carbon markets remains a challenging task.

This study is grounded in existing research on the cointegration between carbon markets and contributes to the literature by extending the analysis to eight mandatory carbon markets, the European Union ETS (hereafter EU ETS), Regional Greenhouse Gas Initiative ETS (RGGI ETS), and California ETS, to assess the interdependencies among future carbon prices as well as three additional carbon markets for spot prices, Canada (Quebec ETS), Korea (South Korean ETS) and China (three Chinese Pilots ETS, notably Shenzhen, Guangdong and Hubei). The data range from August 2011 to August 2019 and from January 2015 to June 2020 for future and spot prices, respectively. Rather than relying on traditional cointegration models such as Vector Error-Correction Model (VECM) and Vector Autoregressive (VAR) models, we measured the dependency across the different trading schemes using tail dependence (Frahm et al., 2005). Tail dependence is computed by fitting a parametric copula family to the data and by subsequently extracting the tail behavior of that copula. Copulas are a very flexible method to model the relationship between different variables through their marginal distributions and dependence structure separately, with the big advantage of accounting for different types of tail dependence from the return series under consideration (Aloui et al., 2013; Boako and Alagidede, 2017; Jondeau and Rockinger, 2006). GARCH-copula models have been extensively adopted in carbon pricing studies (Yu et al., 2020; Uddin et al., 2018; Wu and Hu, 2014). We followed these studies and first estimated, for each pair, the full-range tail dependence copulas through both lower and upper tail and tail asymmetry. Then, we selected the best copula model over the usual GARCH model based on the goodness-of-fit tests developed by Kojadinovic et al. (2010).

The aim of this paper was to provide a thorough analysis of the dependence structure between prices in carbon markets around the world. Our main contribution is twofold. First, we investigated the dependence structure of prices across eight different carbon markets around the world. This significantly contributes to the available literature since, to the best of our knowledge, previous studies investigating dependence structure only included two markets. Second, we also extend the research to a very long time period which has never been explored. This contribution can help reduce price discrepancies across different markets to achieve the ultimate objective of a global, worldwide carbon emission trading scheme. Based on the assumption that the environmental cost of emitting one ton of CO2 should be identical everywhere on Earth, price discrepancies between different markets might generate issues, such as carbon leakage, that would hinder the benefits of climate actions. Third, we applied five different copulas compared to previous studies which were limited to a single copula. The adoption of five different copulas strengthens the degree and structure of dependence, ensuring that any type of transformation is less likely to change it. Compared to multivariate GARCH-type models, copula-based GARCH models can better describe the nonlinear risk spillovers between the existing markets.

Our study showed that the European carbon market exhibited a positive tail dependence with uprising carbon markets (South Korea and Chinese pilot carbon markets), while the latter exhibited zero or weak tail dependence with the RGGI, California and Quebec carbon markets. In addition, a positive dependence was found among the RGGI, California and Quebec carbon markets, which might be due to existing linkage practices. Similarly, the Asian carbon markets are more likely to be dependent on each other. Our results suggested that the regional dependence structure, rather than the emergence of a global carbon market, has been lobbied for by several stakeholders. This clearly suggests the need for alternative policies to reach the ultimate goal of a global carbon market.

The remainder of this study is organized as follows. Section 2 provides an overview of the background of the study by describing methodologies to measure stochastic dependencies in carbon markets in the literature. Section 3 presents the methodology for measuring tail dependencies and introduces the copula model. Section 4 describes the data sources and empirical settings. Section 5 reports the empirical results. The final section concludes the paper.

2.2 Background

For decades, economic theory has advocated for the use of carbon financial instruments to reduce carbon emissions through fixed instruments known as carbon taxes or quantity instruments known as emissions trading contracts (Weitzman, 1974; Newell and Pizer, 2003; Metcalf and Weisbach, 2009; Keohane, 2009; Aldy and Pizer, 2015; Schmalensee and Stavins, 2017). Carbon markets have been integrated into international climate agreements since the Kyoto protocol era under the clean development mechanism, joint implementation and international emissions trading (Capoor and Ambrosi, 2007). The motivation for this study stems from both political and economic dimensions. The world is witnessing the proliferation of carbon markets globally. The European Union Emissions Trading System (EU ETS) is the first and largest one, covering 11,000 emitters across all EU member states, as well as Norway, Iceland and Liechtenstein. California and Quebec share a market, which Ontario, Manitoba and provinces in Brazil and Mexico plan to join. Major Asian economies are following the trend, including Japan, South Korea, China, Kazakhstan, and India (Fankhauser, 2011; Jotzo et al., 2013; Wang, 2013). China is also associated with great potential for large-scale carbon trading. China has recently set up its national cap-and-trade system in June 2021, comprising more than 7,000 emitters. Since 2013, China has launched seven pilot carbon markets in Shenzhen, Beijing, Shanghai, Guangdong, Tianjin, Hubei, and Chongqing (Han et al., 2012; Lo, 2012). Coupled with the above, several countries that ratified the Paris Agreement expressed their intention to implement carbon markets. Many policymakers argue that the next logical step is to combine cap-and-trade efforts into one global carbon market. According to prevailing economic theory, linking markets together should promote trading, smooth financial flows and lower the overall cost of reducing emissions (Nordhaus, 1991; Golombek and Braten, 1994; Westskog, 1996; Jacoby et al., 1997; Bredin and Parsons, 2016; Grüll and Taschini, 2012). Rosendahl and Strand (2011) study Clean Development Mechanism (CDM) markets and note that higher market segregation leads to more carbon leakage, incentivizing a better link between trading systems. A global price on carbon emissions would emerge without the need for long and fractious diplomatic negotiations (Green et al., 2014). Before even embarking on a global carbon market, it is crucial to assess the dependence among the existing ones. This has not been widely studied in the literature; our study aims to fill that gap.

A second motivation for the study is based on the increasing attention given to linking carbon markets. Linkages across carbon markets have not escaped policy makers discussions or scholars' attention. To date, some links have been formed, such as the approved integration of the Swiss ETS by the EU ETS. California's carbon market also has an established link with the Quebec carbon market. Jotzo and Betz (2009) evaluated a plan to bilaterally integrate the Australian ETS with the EU ETS, which was afterwards abandoned in 2012. The impact of linking the EU ETS to the U.S. system was evaluated in Zetterberg et al. (2012). The studies of Marschinski et al. (2012) and Hübler et al. (2014) investigated a proposal for integrating the EU ETS with a Chinese ETS. Similarly, Gavard et al. (2016) modeled a sectoral ETS on electricity and energy-intensive industries in the EU, the U.S. and China, simulating different linkage scenarios. Empirical evidence also suggested a multiregional integrated ETS in which the EU ETS takes part (Anger, 2008; Dellink et al., 2014; Yu and Xu, 2017). Ellerman and Trotignon (2009) investigated cross-border trading and borrowing in the EU ETS and found that there were widespread trading activities as well as preconditioned efficient abatement costs.

The literature on carbon market integration has grown significantly over the last decade. Three dimensions of the carbon markets' integration and dependency have been extensively studied: carbon prices in a single market, bilateral market integration and dependence on other energy commodities. Different methods have been used in all these studies. Chevallier et al. (2010) employed autoregressive methods to measure the cointegration between European Union Allowances (EUA) futures and spot prices. Rittler (2012) measured spillover effects from futures to the spot market using 10-minute and 30-minute data for the EU carbon market. Bredin and Parsons (2016) studied the term structure between spot and future carbon prices and highlighted the fact that spot prices were higher than future prices until the financial crisis of 2008. The relationship between EUA and CERs has also been studied, and a positive spillover effect was identified. Kanamura (2016) adopted a supply and demand correlation model to examine the EUA and CER returns integration. Trück et al. (2014) added to the empirical analysis of the relationship between EUA futures and spot contracts traded on the EEX and presented a convenience yield model for the volatilities between the two assets. Zhu et al. (2020a) adopted a vine copula approach to measure the risks and spillovers in Chinese pilot carbon markets and found that the conditional value at risk (CVaR) was a better measure than traditional risk. Wu and Hu (2014) explored the dynamic interdependence between European carbon spot and futures prices using the copula-GARCH model. Hu et al. (2015) investigated the dependency characteristics of EU carbon markets using the R-vine copula model and found that R-vine copula methods could better depict the dependency structure of the carbon market.

As highlighted here above, GARCH and copula models have been extensively used in the carbon markets literature. To this set of studies, we may also add Zeng et al. (2021), who adopted the copula approach to analyze the dynamic volatility spillover effect between the (EUA) and CER markets during the second and third phases of trading of the European Emission Trading System, showing that there was a spillover effect across the two carbon markets. Benz and Trück (2009) further captured the regime changes in the EU ETS through an AR-GARCH Markov switching price return model. Paolella and Taschini (2008) measured the tails and volatility clustering between the U.S. SO2 permits and EUA price returns through GARCH modeling. Chevallier et al. (2011) used a Dynamic Conditional Correlation (DCC) model to analyze the dynamic correlation between EUAs and CERs and found that the correlation coefficient between the two markets changes dynamically over time in the range of [0.01; 0.90]. Chun (2018) used a DCC(1,1) model to analyze the volatility spillover effect between the market prices of the EU ETS and Chinese carbon market for the period ranging from 2014 to 2017. The results demonstrated that there were agglomeration effects in the two markets, but the market concentration and price volatility were more significant.

The GARCH-Copula methodology has also been applied in other energy commodities' markets to assess tail dependency. For example, Uddin et al. (2018) modeled the multivariate tail dependence structure and spillover effects across energy commodities, such as crude oil, natural gas, ethanol, heating oil, coal and gasoline. Yu et al. (2020) used the copula and VAR-BEKK-GARCH models to study the volatility spillovers between the oil and stock markets. Balcılar et al. (2016) relied on the MS-DCC-GARCH model to find time-varying cross-market correlations and volatility spillover effects between EU carbon futures prices and electricity, coal and natural gas futures prices.

Based on the above evidence, we deduced that GARCH models have been the most favored and adopted models in carbon market integration studies. Among these investigations, some went even further by including copula-based modeling. Our contribution falls into that category. The widespread finance literature vouch for two-step copula modeling, which involves marginal estimations prior to deducting the dependence parameters (Embrechts et al., 2002; Meucci, 2011). Copula models address the drawbacks of the Pearson correlation coefficient, as they do not require random variables to be elliptically distributed. They are also invariant to increasing and continuous transformations (Durante et al., 2010; Schmid et al., 2010; Cai and Wei, 2012). For the purpose of this study, we selected a methodology that has been used in most seminal papers and is known to be robust and appropriate to assess the dependence structure across carbon markets.

While the above empirical studies focused on carbon price models and the empirical analysis of a single carbon market, they did not assess the characteristics of price dependency across different carbon markets. With the emergence of new carbon markets around the world, there is a need to consider in a wider range of carbon markets, rather than investigating bilateral integration as was done in previous studies. By studying both spot and future prices across eight carbon markets, we provide novel insight into the cointegration of carbon markets. Furthermore, given the extensive application of the GARCH-Copula methodology in energy commodities and carbon markets, we relied on the best methodology, to the best of our knowledge, to test the empirical integration of the global carbon market.

2.3 Methodology

The primary objective of this study is to test the dependence structure across carbon markets using the EGARCH copula model, which has been extensively adopted in the literature (see Chevallier et al. (2011); Arouri et al. (2012); Mou (2019); Zhu et al. (2019b)). This modeling approach is advantageous because it allows us to separately model the margins (GARCH-based model) and the association structure of different variables (copula models). Furthermore, the model provides more flexibility for constructing the joint distribution of multiple returns. Copulas are favorable for assessing the dependence structure since they allow for greater flexibility in modeling and estimating margins compared to multivariate distributions. Both the degree and structure of dependence are also considered. Simple linear correlation analyses only examine how carbon prices move together on average across marginal distributions assuming multivariate normality. In the following subsections, the copula functions are briefly explained. The specifications of the EGARCH model are provided and the five copula estimations are discussed.

2.3.1 Copulas

In this study, we employed the two-step estimation process of copula models suggested by Aloui et al. (2013). A copula is a function that combines marginal distributions to form a joint multivariate distribution (Min and Czado, 2010). The concept was initially introduced by Sklar (1996) but has only gained popularity in modeling financial or economic variables over the last two decades.[1] Sklar (1996) showed that the concept of copulas could deviate from a rich set of joint distributions. Assuming that $X = (X_1.....X_d)$ is a random vector with continuous marginal cumulative distribution functions $F_1.....F_d$, Sklar (1996) shows that the joint distribution H of X could be represented as:

$$H(X) = C(F_1(x_1), ..., F_d(x_d)) \tag{2.1}$$

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[1] For an introduction to copulas see Nelsen et al. (2001), Joe (2006). For applications to various issues in financial economics and econometrics, see Cherubini et al. (2011), Demarta and McNeil (2005), Frey and McNeil (2003) and Hull and White (2006).

in terms of a unique function $C : [0,1]^d \rightarrow [0,1]$ called a copula. Copula functions can conveniently construct a multivariate joint distribution by first specifying the marginal univariate distributions and then investigating the dependence structure between variables with different copula functions. Moreover, tail dependence can be well described by copulas. Usually, two measurements are applied to evaluate tail dependence: the upper and lower tail dependence coefficients. They function well regardless of whether the markets are crashing or booming. By assuming that X and Y are random variables with marginal distribution functions F and G, it is possible to compute the coefficient of the lower tail dependence, λ_L:

$$\lambda_L = Lim_{t \rightarrow 0+} Pr[Y \leq G^{-1}(t) \mid X \leq F^{-1}(t)] \tag{2.2}$$

which measures the probability of observing a lower Y if the condition X itself is lower. In contrast, the coefficient of upper tail dependence λ_U can be estimated by:

$$\lambda_U = Lim_{t \rightarrow 1-} Pr[Y > G^{-1}(t) \mid X > F^{-1}(t)] \tag{2.3}$$

When the value of lower tail dependence is the same as the value of upper tail dependence, we conclude that there is symmetric tail dependence between the two variables. In all other cases, the dependence is considered asymmetric. This approach constitutes an efficient way to order copulas. Moreover, if λ_U of C_2 is greater than λ_U of C_1, it indicates that copula C_2 is more concordant than C_1.

2.3.2 Marginal Specification

Dependencies in carbon markets can be examined by combining these copula functions with a GARCH-type model including conditional heteroscedasticity, since this model successfully describes the characteristics of volatility clustering in carbon allowance prices. The GARCH family, e.g., EGARCH, MGARCH, GJR-GARCH, TGARCH and ARMA-GARCH models, has been extensively adopted by studies on carbon prices (see, for instance, Wang et al. (2019a); Fu and Zheng (2020); Bulai et al. (2021); Zhang and Wu (2022)). Along with the GJR-GARCH and the TGARCH, the EGARCH model has the very interesting feature of accommodating asymmetric reactions of volatility to positive and negative shocks. One differentiating element in favor of the EGARCH is the log transformation of the conditional variance equation. Most studies use the EGARCH model to capture the leverage effects of financial time series (see previous section).

The conditional variance and autocorrelation of the carbon price returns can be captured through an ARMA-EGARCH model, which can be defined as:

$$r_t = \mu + \Sigma_{i=1}^{p} \phi_i r_{t-i} + \Sigma_{j=i}^{q} \theta_j \varepsilon_{t-j} + \varepsilon_t \tag{2.4}$$

$$\varepsilon_t = \sigma_t z_t \tag{2.5}$$

$$log(\sigma_t^2) = \omega + \Sigma_{s=1}^{m} [\alpha_s z_{t-s} + (\gamma_s \mid z_{t-s} \mid - E \mid z_{t-s} \mid)] + \Sigma_{s=1}^{m} \beta_s log(\sigma_t^2) \tag{2.6}$$

Equation (2.4) is the mean equation, Equation (2.5) shows the relationship between error and conditional variance of price log-return and Equation (2.6) is the variance equation. In the mean model in Equation (2.4), r_t is the log-returns of carbon prices from the different carbon markets. μ is a constant term, ϕ is the ith autoregressive coefficient, θ_j is the $i$ith moving average coefficient, and ε_t is the error term at time t. p and q are the orders of autoregressive and moving average terms in the mean model, respectively.

In the distribution model in Equation (2.5), we refer to Nelsen et al. (2001) and assume that the error term ε_t follows the generalized error distribution (GED). In the variance model in Equation (2.6), σ_t^2 is the conditional variance prediction at time t, ω is the variance intercept parameter, and β_s is the parameter indicating the ARCH effect in volatility. α_s captures the sign effect. γ_s is the size effect. m and n are the orders of the GARCH equation.

The appropriate p and q for each of the log-returns of the carbon markets are identified based on the minimum value of the Akaike Information Criterion (AIC) and Schwarz Bayesian Criterion (SBC).

2.3.3 Conditional Dependence Structure Specification

In this study, we considered both the symmetric and the asymmetric structure dependence between the variables. For a given set of marginals above, the copula model is used to investigate the conditional dependence structure among carbon markets. We focused on two types of copulas: elliptical copulas (i.e., normal and Student-*t*) and Archimedean copulas (i.e., Gumbel, Frank and Clayton):

For all u, v in $[0, 1]$, the bivariate normal copula is defined by

$$C(u,v) = \int_{-\infty}^{\phi^{-1}(u)} \int_{-\infty}^{\phi^{-1}(v)} \frac{1}{2\pi\sqrt{1-\theta^2}} exp(-\frac{s^2 - 2\theta st + t^2}{2(1-\theta^2)}) dsdt \tag{2.7}$$

where ϕ represents the univariate standard normal distribution function and θ is the linear correlation coefficient restricted in the interval [-1,1]. The bivariate

Student-t copula is defined by:

$$C(u,v) = \int_{-\infty}^{t_v^{-1}(u)} \int_{-\infty}^{t_v^{-1}(v)} \frac{1}{2\pi\sqrt{1-\theta^2}} exp(1 + \frac{s^2 - 2\theta st + t^2}{(v(1-\theta^2)})^{-(v+2)/2} dsdt \quad (2.8)$$

where $t_v^{-1}(u)$ denotes the inverse of the cumulative distribution function (CDF) of the standard univariate Student-t distribution with v degrees of freedom. The Gumbel copula is an asymmetric copula with a higher probability concentrated in the right tail. It can be expressed by:

$$C(u,v) = exp\{-[(-ln\ u)^{\theta} + (ln\ v)^{\theta}]^{1/\theta}\}, \theta \in [1, +\infty]$$

The Frank copula is defined as:

$$C(u,v) = -\frac{1}{\theta} ln \left(1 + \frac{exp(-\theta u) - 1)(exp(-\theta v)) - 1}{exp(-\theta) - 1}\right), \theta \in [-\infty, +\infty]$$

The Clayton copula is defined as:

$$C(u,v) = (u^{-\theta} + v^{-\theta} - 1)^{-1/\theta}, \theta \in [0, +\infty]$$

In the finance literature, elliptical copulas are most frequently applied because they have been shown to offer straightforward implications (Nikoloulopoulos et al., 2012; Boako et al., 2019; Wen et al., 2019; Naeem et al., 2020). The normal and student copulas can be classified into this family because they are based on an elliptical contoured distribution. Gaussian copulas are symmetric and do not capture tail dependence, while Student-t copulas can reflect extreme dependence between variables. Archimedean copulas such as the Frank copula also tend to be symmetric and can provide the full range of dependence estimation for marginals exposed to weak tail dependence. However, the Gumbel and Clayton copulas are asymmetric and are not derived from multivariate distributions. Therefore, they are typically used to capture asymmetry between lower and upper tail dependencies. For example, Clayton copulas show greater dependence in the negative tail than in the positive tail, while Gumbel copulas show the opposite. Nevertheless, for both the Clayton and Gumbel copulas, the greater the value of θ is, the greater the dependence between the variables.

2.3.4 Estimation

In a second step, we estimate the parameters of the copulas based on the quasi-maximum likelihood (QML) or pseudomaximum likelihood (PML) methods and filter the returns. Following Aloui et al. (2013), we estimate the marginals F_x and G_y using their empirical CDF $\hat{F}_x$ and $\hat{G}_y$ defined as:

$$\hat{F}_x = \frac{1}{n}\sum_{j=1}^{n} 1\{X_i < x\} \text{and} \hat{G}_y = \frac{1}{n}\sum_{j=1}^{n} 1\{Y_i < y\} \tag{2.9}$$

In the implementation, $\hat{F}_x$ and $\hat{G}_y$ are replaced by $n/(n+1)$ uniform variates using the empirical CDF of each marginal distribution to ensure that the first-order condition of the log-likelihood function of the joint distribution is well defined for all finite n. Here, X_i and Y_i are the standardized residuals estimated from the first step. Then, we transform the observations into uniform variates using the empirical CDF of each marginal distribution and estimate the unknown parameter θ of the copula.

2.4 Data

In this study, we evaluated the dependence structure among both future and spot contracts of carbon allowances around the world. Although an increasing number of carbon markets have been established around the world, the trading of future contracts is still at an early stage for most of them, except for the EU, RGGI and California ETSs. For example, the Chinese carbon markets only started offering future contracts in 2021. For this reason, we could only assess the dependence structure for future contracts for EUA, RGGI and Californian allowances. The future contract prices were retrieved from Refinitiv for future contracts, with EUA being traded on the European Energy Exchange (EEX). RGGI emission contracts are traded on the New York Mercantile Exchange (NYMEX) platform. California allowances future contracts are traded on NYMEX. For future contracts, a 1-month rolling approach was adopted to obtain the price time series. We obtained future contract prices for the period ranging from August 2011 to August 2019, amounting to approximately 2048 observations. For all future contracts, we only focused on December maturity for each year; there is a clear consensus in the literature that December maturity dominates all other maturities in terms of trading activity (see Mizrach (2012) for a thorough discussion).

Regarding spot prices, we included additional carbon markets since they were more widely available. However, most of them were very recent and, thus, did not include as many data points as future contracts. For the EUA spot prices, data were obtained from the EEX platform. Additionally, we included spot prices from California, Quebec and RGGI; the data were provided by Argus. Only the three oldest Chinese pilot carbon markets (Guangdong, Hubei and Shenzhen) were included in our study. These pilot markets were also associated with the largest market activity and provided sufficient and high-quality

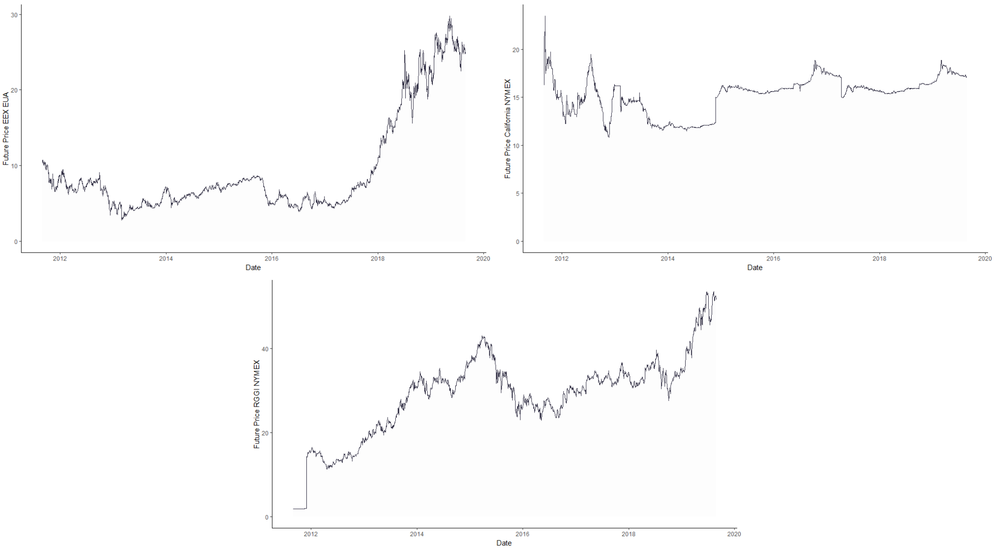

Figure 2.1: Daily Future Prices of Carbon Allowances.
The figures show the daily future prices for EU, California and RGGI , from left to right and top to bottom, respectively.

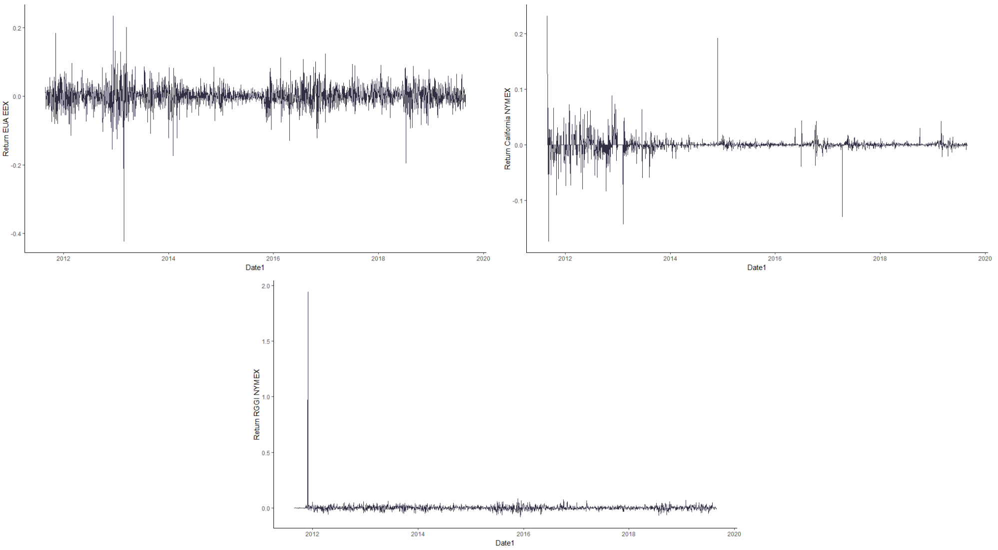

Figure 2.2: Daily Returns of Future Contracts of Carbon Allowances.
The figures show the returns for future contracts for EU, California and RGGI, from left to right and top to bottom, respectively.

data for our analysis. Since the Sichuan and Fujian markets began to operate on December 16, 2016 and December 22, 2016, respectively, we did not include them due to the lack of available data points. The data for the Chinese and South Korean carbon allowances were obtained from the International Emissions Trading Association (IETA) platform. For spot prices, data were analyzed for the period ranging from January 2015 to June 2020, including 1048 observations. Overall and to the best of our knowledge, thanks to these different data sources, this was the most comprehensive analysis both in terms of the number of markets and the length of the time period.

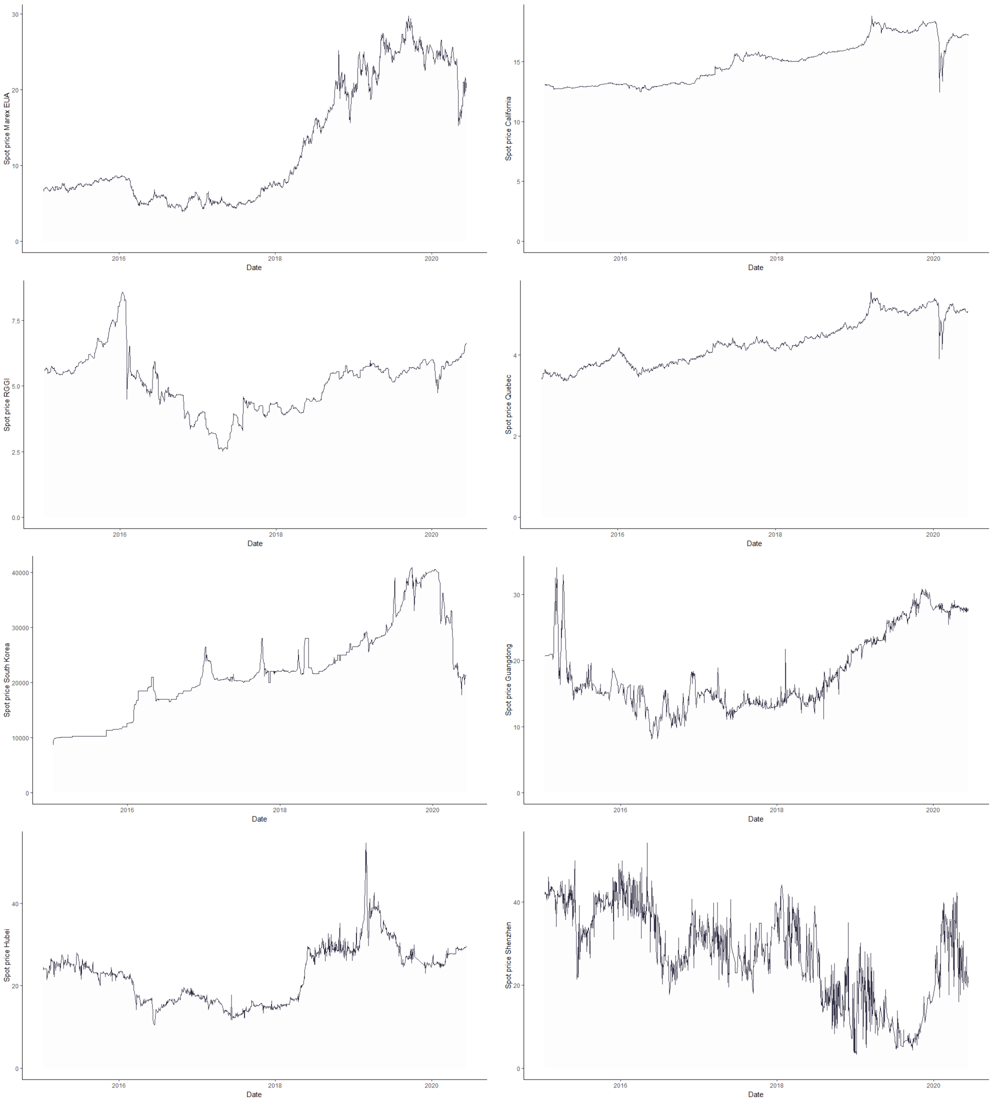

Figure 2.3: Daily Spot Prices of Carbon Allowances.
The figures show the daily spot prices for EU, California, RGGI, Quebec, South Korea, Guandong, Hubei and Shenzhen, from left to right and top to bottom.

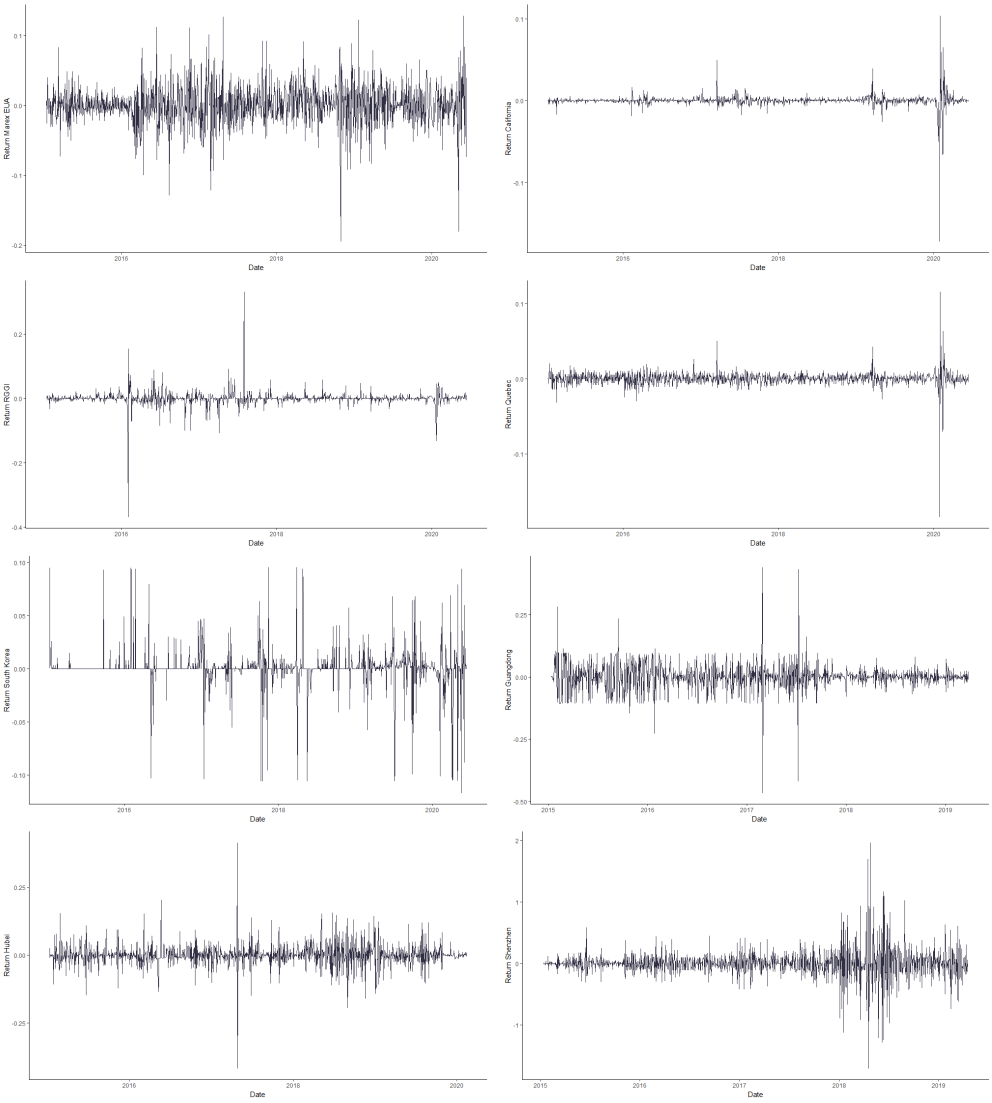

Figure 2.4: Daily Returns of Spot Contracts of Carbon Allowance.
The figures show the returns of spot contracts for EU, California, RGGI, Quebec, South Korea, Guandong, Hubei and Shenzhen, from left to right and top to bottom.

In all cases, the price returns were calculated as the first differences of the log of the price indices. Let S_t denote the log of the spot price at time t and $\triangle S_t = S_t - S_{t-1}$ denote the corresponding log return. Similarly, F_t is the log of the future price, and $\triangle F_t = F_t - F_{t-1}$ is the corresponding log-return

The descriptive statistics of the futures and spot price series are reported in Tables 2.1 and 2.2, respectively. We observed kurtosis > 3 for all the variables, indicating that none of the distributions could be considered normal, as suggested by the fourth moment. In addition, the returns distributions were negatively skewed for two EU ETS contracts and RGGI and positively skewed for the remainder. Skewness for spot contracts was negative for all variables. The results of the Jarque-Bera test led us to reject the null hypothesis of normality in all cases. The results of the Ljung-Box Q statistics also indicated serial correlation in the time series for all variables.

Table 2.1: Descriptive statistics (Futures).

	EU	RGGI	California
Mean	0.00004	0.0016	2.48E-05
Median	0.0008	0.0003	0
Maximum	0.2347	1.9420	0.2323
Minimum	-0.4223	-0.0798	-0.1729
SD	0.0337	0.0461	0.0145
Skewness	-0.9072	36.3340	1.165
Kurtosis	15.736	1526.917	72.111
Jarque-Bera	21513***	20028039***	446181
Q	92.602***	3.4636***	90.573***

This table shows the descriptive statistics for each future contract in our sample. The table includes statistics on moments, median, maximum and minimum, as well as the test statistics associated with the Jarque-Bera and Ljung-Box Q tests.

Table 2.2: Descriptive Statistics (Spot)

	EUA EEX	California	Quebec	RGGI	South Korea	Shenzhen	Guangdong	Hubei
Mean	0.0008	0.0002	0.0001	0.0001	0.0007	0.0015	0.0006	0.0002
Median	0	0	0	0	0	-0.000005	0.0006	-0.0004
Maximum	0.1282	0.1036	0.1158	0.3322	0.0953	1.9637	0.4405	0.4124
Minimum	-0.1945	-0.1714	-0.1840	-0.3677	-0.1165	-1.7062	-0.4653	-0.4155
SD	0.02891	0.0083	0.0097	0.0207	0.0189	0.2415	0.0543	0.0414
Skewness	-0.3150	-6.1774	-4.6813	-1.4833	-1.1799	0.4103	-0.0375	0.1105
Kurtosis	4.3965	173.6253	122.3088	127.5131	16.4305	13.1370	15.9623	17.4204
Jarque Bera	1135.637***	1740985.656***	864643.0067***	934823.67***	15839.6414***	7990.6963***	11569.6667***	16424.1238***
Q	0.014826	0.014826	6.3623***	9.7216***	21.17***	249.96***	37.786***	89.007***

This table shows the descriptive statistics for each spot contract in our sample. The table includes statistics on moments, median, maximum and minimum, as well as the test statistics associated with the Jarque-Bera and Ljung-Box Q tests.

2.5 Empirical Results

2.5.1 Main Results

Since the carbon price time series exhibited peaks, fat tails, autocorrelation and the property of conditional heteroscedasticity, the residual sequence of the [0, 1] uniform distribution was obtained from carbon price returns before application of the copula model, as proposed by Zhu et al. (2020a).[2] Based on the parameter estimation of the mean equation, the return μ on carbon emissions for future contracts in the EU, RGGI and California was positive, which indicates that the carbon price is relatively stable during the sample period. In contrast, the return on carbon emissions for spot contracts was near zero or negative, indicating a lack of trading activity. From the mean equation, the different combinations with lags from 0 to 4 were taken, and the ARMA (p, q) with the lowest AIC was selected. Based on the mean equation, the EU, RGGI and California future returns for carbon emissions were subject to ARMA (2,2), (2,2) and (2,1), respectively. For spot returns, the EU ETS had ARMA (0,0), California ETS (4,2), Quebec ETS (4,2), RGGI ETS (0,0), South Korea, Shenzhen, Guangdong and Hubei with ARMA (2,2). Tables 2.3 and 2.4 report the estimation results. As seen in these tables, all the coefficients of the EGARCH term (β) with values close to 1 were statistically significant at the 1% level. Moreover, the coefficients of the asymmetric effect (γ) were statistically significant at the 1% level with negative values. The shape parameters were also statistically significant at the 1% level with values less than 2, suggesting that the tails of the error terms were heavier compared to the normal distribution. The $Q(s)$ and $Q^2(s)$ statistics were used to validate the empirical results

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[2] The price returns series were tested for stationarity using the Augmented Dickey-Fuller test (ADF). The resulting p values led to the rejection of the null hypothesis assuming the presence of a unit root in the returns series, meaning that the returns series were, as expected, stationary. The results are available upon request.

of the EGARCH models.[3] In a second step, we transformed the standardized residuals obtained from the EGARCH model into uniform variates based on the empirical CDFs. By applying this step, we obtained a vector of filtered returns to estimate the copula functions for carbon markets. Then, we checked the rank correlation coefficients for carbon market dependence. Figures 2.5 and 2.6 summarize Kendall's tau and Spearman's rho statistics for the sample. There was a significant negative correlation between EUA and RGGI for future contracts. For spot prices, greater significant correlations were observed. The greatest positive correlation was between Quebec and Californian carbon allowances, which might be due to the existing link between these two markets. California and Quebec also exhibited a positive but weak correlation with the EU ETS. RGGI did not have any significant link with the western markets; rather, weak correlation was observed between South Korea and Guangdong. The South Korean ETS was weakly correlated with those of Hubei and Shenzhen.

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[3] The $Q(s)$ statistic at lag s is a test statistic that has an asymptotic Chi-square distribution with degrees of freedom equal to the difference in the number of autocorrelations and the number of parameters. The null hypothesis of the corresponding test is that there is no autocorrelation up to lag s for standardized residuals.

Table 2.3: Estimations of EGARCH Models (Future)

	EU	RGGI	California
Mean Equation			
μ	0.0085***	0.0019***	-0.0000***
	(0.0003)	(0.0000)	(0.0000)
AR_1	-0.4183***	0.0104***	0.2200***
	(0.1331)	(0.0002)	(0.0004)
AR_2	-0.7559***	-0.0016***	0.0020***
	(0.0318)	(0.0000)	(0.0000)
MA_1	0.4090***	0.0103***	-0.2198***
	(0.1464)	(0.0002)	(0.0004)
MA_2	0.7014***	-0.0015***	
	(0.3371)	(0.00001)	
Variance Equation			
ω	-0.1158***	-0.6990***	-0.9862***
	(0.0314)	(0.0002)	(0.0466)
α	-0.0199	0.0468***	0.0474
	(0.0148)	(0.0009)	(0.0299)
β	0.9837***	0.9010***	0.9077**
	(0.0044)	(0.0002)	(0.0042)
γ	0.2008***	-0.1400***	0.2744***
	(0.0271)	(0.0000)	(0.0223)
GED Parameter	1.2638***	1.9772***	0.3444***
	(0.0500)	(0.0004)	(0.0100)
Diagnostic			
Q	2.0280	0.6214	0.0646
	[0.15440]	[0.4305]	[0.7992]
$Q^2(10)$	0.8119	0.0006	0.0128
	[0.3675]	[0.9795]	[0.9097]

This table presents the results of the estimations of the EGARCH models for each future contract. All the standard parameter estimates are reported.

Table 2.4: Estimations of EGARCH Models (Spot)

	EU	California	Quebec	RGGI	South Korea	Shenzhen	Guangdong	Hubei
Mean Equation								
μ	0.0006	0	0	0	0	0	0.0004***	-0.0003***
	(0.0005)	(0)	(0)	(0)	(0)	(0.0011)	(0.0001)	(0.00005
AR_1		0.8927***	1.1791***		-0.0957***	-0.2853***	0.6208**	-0.2876***
		(0.0188)	(0.0004)		(0.0002)	(0.0461)	(0.0244)	(0.0327)
AR_2		-0.6471***	-0.7542***		0.0729***	0.0885***	0.0876***	0.1273***
		(0.0002)	(0.0003)		(0.0013)	(0.0459)	(0.0256)	(0.0080)
AR_3			0.4968***					
		(0.0001)	(0.0002)					
AR_4		-0.2883***	0.0720***					
		(0.0001)	(0.0000)					
MA_1		-0.8932***	1.1797***		0.0942***	0.2259***	-0.8775***	0.0789**
		(0.0003)	(0.0003)		(0.0002)	(0.0364)	(0.0205)	(0.0267)
MA_2		0.6472***	0.7547***		0.0083***	-0.2720***	0.0560***	-0.1944***
		(0.0002	(0.0003)		(0.0000)	(0.0530)	(0.0111)	(0.0094)
Variance Equation								
ω	-0.1880***	-0.9928***	-0.3869***	-0.8213***	-1.3200***	-0.1092***	-0.4946***	-1.8842***
	(0.0566)	(0.2809)	(0.1493)	(0.1920)	(0.0121)	(0.0392)	(0.1165)	(0.2845)
α	-0.0271	-0.1317	0.0245	0.0606	-0.0924***	-0.0704**	0.01424	-0.1065**
	(0.0209)	(0.0951)	(0.0869)	(0.0786)	(0.0013)	(0.0302)	(0.0401)	(0.0495)
β	0.9741***	0.9031***	0.9537***	0.9011***	0.9115***	0.9715***	0.9236***	0.7260***
	(0.0077)	(0.0269)	(0.0140)	(0.0267)	(0.0005)	(0.0098)	(0.0177)7	(0.0409)
γ	0.2437***	0.8258***	0.4148***	0.7217***	0.2894***	0.41825***	0.7174***	0.9602***
	(0.0346)	(0.1367)	(0.0766)	(0.1215)	(0.0266)	(0.0549)	(0.0797)	(0.0860)
GED Parameters	1.2763***	0.2815***	0.3306***	0.1180***	0.1430***	1.2538***	1.0537***	0.8727***
	(0.0647)	(0.0068)	(0.0265)	(0.0024)	(0.0051)	(0.0662)	(0.0577)	(0.0426)
Diagnostic								
Q	1.2000	0.00756	8.5860	9.6290	0.1665	0.0553	0.0592	0.5656
	[0.2733]	[0.9307]	[0.0033]	[0.0019]	[0.6832]	[0.8140]	[0.8078]	[0.4520]
$Q^2(10)$	0.3382	0.0075	25.789	0.2612	0.0060	1.5940	0.5329	2.2270
	[0.5608]	[0.9307]	[0.0490]	[0.6093]	[0.9379]	[0.2068]	[0.4654]	[0.1357]

This table presents the results of the estimations of the EGARCH models for each spot contract. All the standard parameter estimates are reported.

By applying the vector filtered returns, we incorporated five copula functions (normal, Student-t, Frank, Gumbel and Clayton) to estimate the dependence parameters θ for the sample. The results are reported in Tables 2.5 and 2.6.

The results showed that for future return series, all outcomes were significant at the 1% level for all copulas. The dependence parameters for EU and Californian allowances were mostly negative and very low. Similar results were found for the dependence structure between EU and RGGI as well. The dependence parameters between California and RGGI were negative, despite the fact that there is a link between markets and their mechanism structure is similar. The results differed from those of Paolella and Taschini (2008) who found a correlation between EUA future prices and SO2 permits.

For the spot return series, a higher dependency was noted throughout the markets. All the copulas had significant results at the 1% level. The EU ETS exhibited a positive dependence with California and Quebec and a negative dependence with RGGI. This indicated that spot prices in the two oldest markets have still not converged after a period of time.

A mixed relationship between the EU ETS and Asian carbon markets was found. Notably, there were positive dependence parameters for the Chinese Shenzhen and Hubei ETSs and negative parameters for the South Korea and Chinese Guangdong ETSs. The results showed that although the EU ETS was the first and one of the largest in the world, it was not highly correlated with the uprising markets, notably in the Asian regions. These results were in line with the findings of Chun (2018) regarding EU and Chinese markets spillover between 2014 and 2017.

The dependence parameters between the U.S. and Asian carbon markets were also mostly negative for the different copulas. Only RGGI and South Korea exhibited a positive relationship. Negative parameters were obtained for Cali-

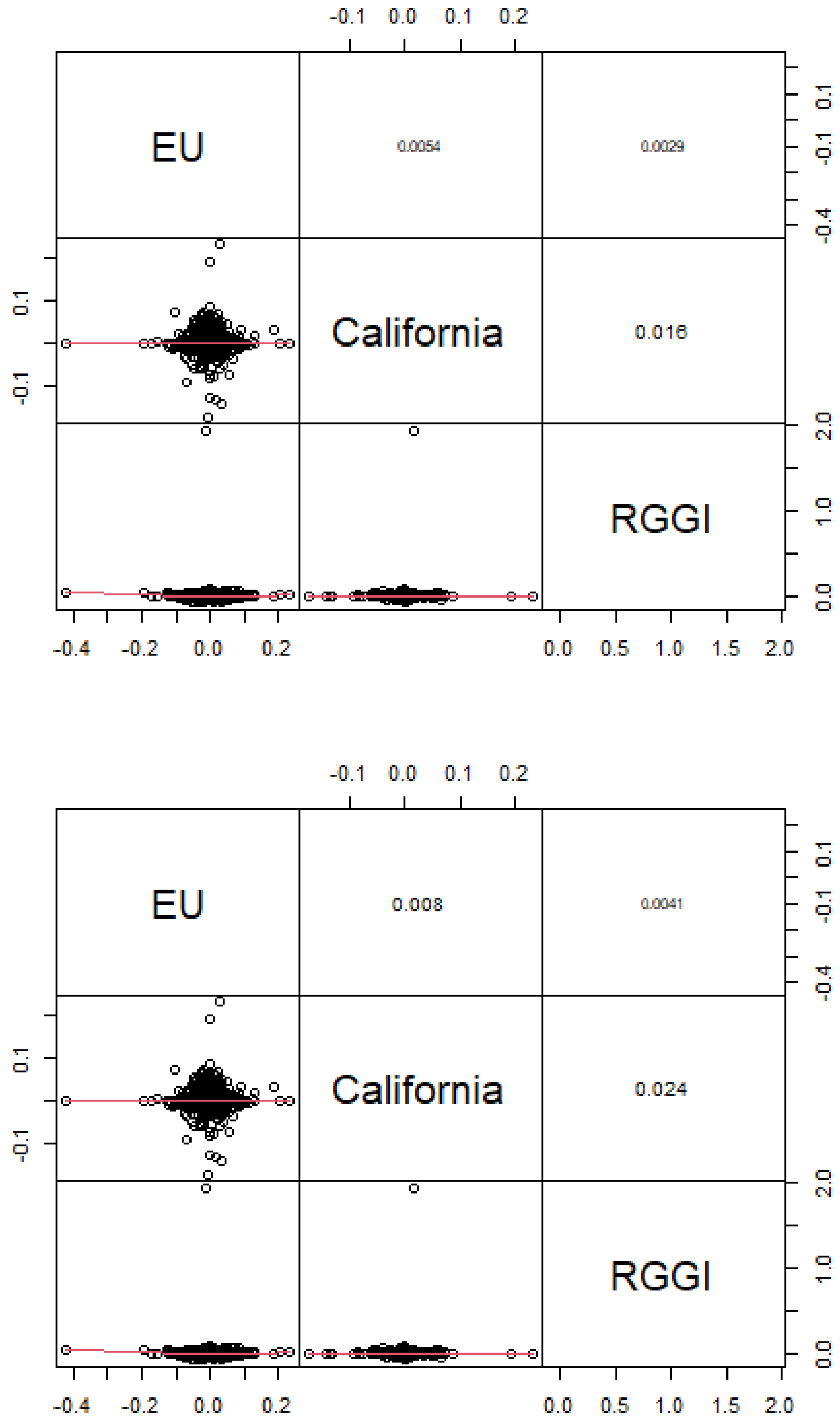

Figure 2.5: Correlations between Future Returns.
Figures showing the Kendall and Spearman's Correlation respectively for Future Contracts

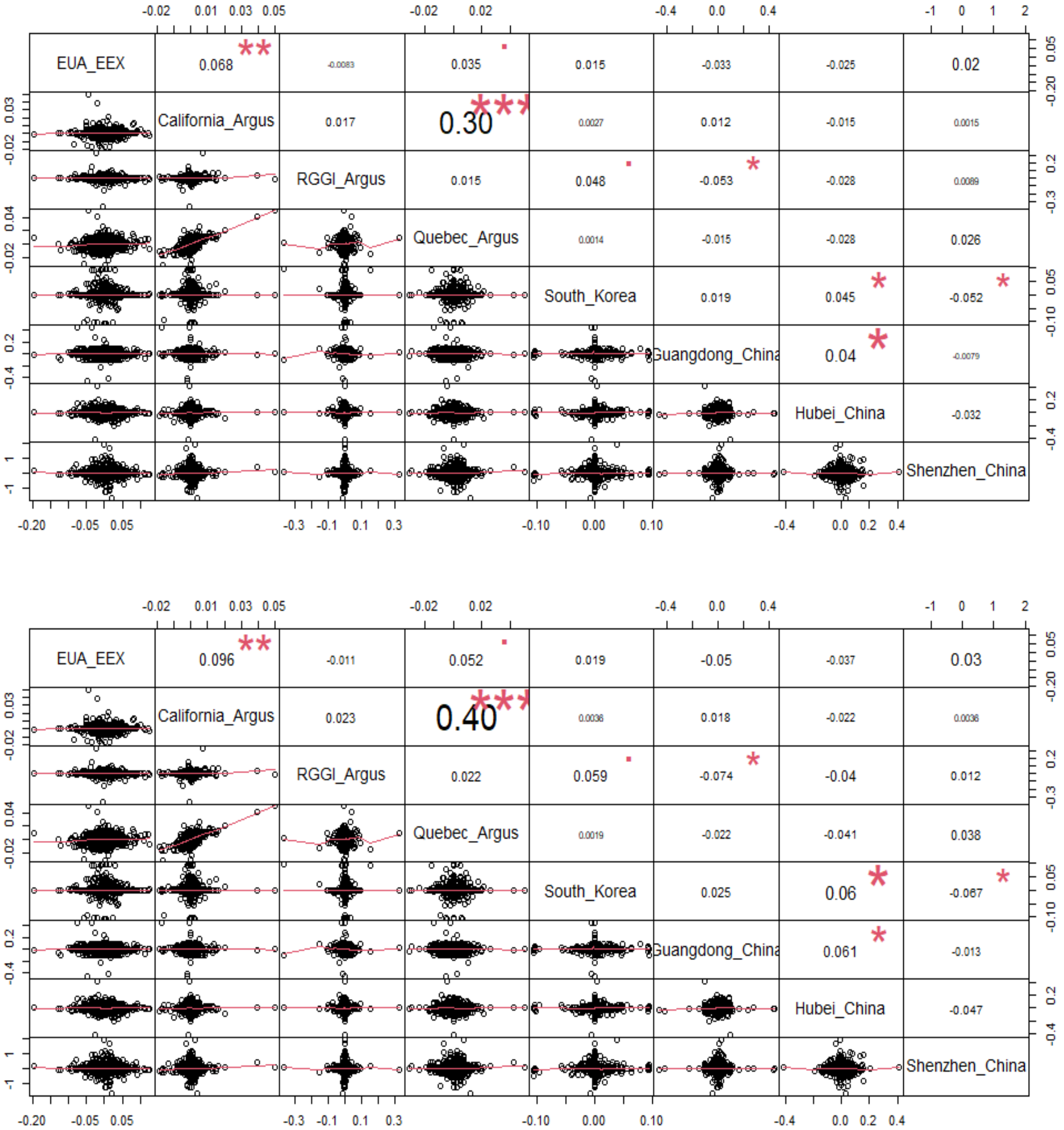

Figure 2.6: Correlations between Spot Returns.

Figures showing the Kendall and Spearman's Correlation for Spot Contracts fornia and RGGI, as was the case for the future return series. However, positive parameters were obtained for the California and Quebec carbon markets, which might be due to the existing link between them. Quebec and RGGI registered negative parameters as well. The Asian carbon markets exhibited positive dependence parameters across the different copulas. This study provided a first snapshot of the dependence structure among carbon markets globally. The results highlighted the low dependency among the markets. Alexeeva and Anger (2016) discussed the globalization of the international carbon market through the mechanism of the International Carbon Action Partnership (ICAP). The European Commission, a founding member of the ICAP, expressed interest in globalizing transactions. However, thus far, no strong signal regarding a potential link and dependency with the EU ETS has emerged. To date, the EU ETS has only been linked with Norway and Switzerland ETSs. A discussion of a link with the Australian ETS was initiated but rather quickly aborted. Ye et al. (2021) also found that the EU carbon market was strongly influenced by the economic policies in the U.S. However, we found that the EU ETS was unlikely to be dependent on the US carbon markets, most notably the California ETS and RGGI ETS.

We expected a dependence structure given that common carbon price drivers across carbon markets were found in the literature (for example, see Chevallier (2012); Hammoudeh et al. (2015); Ji et al. (2019) for EU ETS and energy prices). Previous studies described the strong correlation between carbon markets and commodity markets. Since commodity prices are very similar on an international level, it is likely that the dependence structure among carbon markets is strong since they are influenced level by similar drivers. Our results indicated a weak dependency, so there is a need to expand and compare the extent of the spillover of international commodities on carbon markets.

Ranson and Stavins (2016) noted that the single most significant predictor of systems linking may be geographic proximity. Existing linkages are mostly based on geographical criteria. The EU Member States are linked through the EU ETS. Norway and Switzerland are positioned in geographic proximity. Quebec and California are linked, as are the Australian and New Zealand ETSs. The relationship between geography and dependence was reflected in our findings. The Asian carbon markets, South Korean ETS and Chinese ETS were positively dependent. The California ETS and RGGI ETS exhibited stronger dependence (despite being negative) than the other pairs tested. Thus, our results corroborated the findings of Ranson and Stavins (2016).

Table 2.5: Correlation of Estimates of the Dependence of the Exchanges (Futures)

Exchanges	Normal	Student-t	Frank	Gumbel	Clayton
EU - California	-0.005217(0.023)***	-0.009409(0.027)***	-0.06562(0.146)***	1.008(0.014)***	-0.0143(0.034)***
EU - RGGI	-0.01238(0.021)***	-0.01183(0.023)***	-0.04584(0.132)***	1.005(0.015)***	-0.0102(0.03)***
California - RGGI	-0.02121(0.025)***	-0.02155(0.026)***	-0.1217(0.149)***	1.013 (0.017)***	-0.02597(0.035)***

This table presents the results of the correlation of the estimates of the dependence of the different exchanges for future contracts by pair of exchange. We incorporated five copula functions (normal, Student-t, Frank, Gumbel and Clayton) in order to estimate the dependence parameters θ for the sample.

Table 2.6: Correlation of Estimates of the Dependence of the Exchanges (Spot)

Exchanges	Normal	student's t	Frank	Gumbel	Clayton
EU - California	0.05256 (0.029)***	0.05239 (0.029)***	0.2516 (0.172)***	1.024 (0.017)***	0.05923 (0.04)***
EUA - RGGI	-0.06731 (0.04)***	-0.06632 (0.042)***	-0.2485 (0.238)***	1.016 (0.026)***	-0.0519 (0.05)***
EUA - Quebec	0.06918 (0.03)***	0.06912 (0.03)***	0.3723 (0.173)***	1.019 (0.019)***	0.0845 (0.041)***
EUA - South Korea	0.005239 (0.03)***	0.004236 (0.029)***	-0.02986 (0.169)***	1 (0.016)***	-0.005118 (0.039)***
EUA - China Shenzhen	-0.03579 (0.03)***	-0.03499 (0.032)***	-0.184 (0.177)***	1.029 (0.018)***	-0.03837 (0.04)***
EUA - China Guangdong	-0.03705 (0.03)***	-0.03718 (0.034)***	-0.237 (0.193)***	1 (0.018)***	-0.05316 (0.035)***
EUA - China Hubei	0.01842 (0.03)***	0.01937 (0.03)***	0.1054 (0.168)***	1.009 (0.014)***	0.04213 (0.032)***
California - RGGI	-0.01939 (0.04)***	-0.01916 (0.042)***	-0.08596 (0.239)***	1.008 (0.02)***	-0.01946 (0.052)***
California - Quebec	0.09906 (0.02)***	0.09722 (0.032)***	0.5861 (0.154)***	1.086 (0.018)***	0.1354 (0.044)***
California s - South Korea	-0.01086 (0.03)***	-0.01356 (0.029)***	-0.1285 (0.166)***	1.009 (0.016)***	-0.02916 (0.038)***
California Argus - China Shenzhen	-0.03858 (0.03)***	-0.02897 (0.031)***	-0.154 (0.179)***	1.028 (0.018)***	-0.0332 (0.04)***
California - China Guangdong	-0.02875 (0.03)***	-0.006216 (0.041)***	-0.1952 (0.184)***	1.021 (0.021)***	-0.04105 (0.039)***
California - China Hubei	0.01413 (0.03)***	0.04192 (0.042)***	0.06635 (0.172)***	1.008 (0.018)***	0.01543 (0.036)***
RGGI - Quebec	-0.005927 (0.04)***	-0.002926 (0.042)***	-0.04782 (0.237)***	1.006 (0.027)***	-0.01262 (0.053)***
RGGI - South Korea	0.03829 (0.04)***	-0.005644 (0.042)***	0.2955 (0.231)***	1.006 (0.025)***	0.07129 (0.046)***
RGGI - China Shenzhen	-0.006798 (0.04)***	-0.001988 (0.044)***	0.07998 (0.733)***	1.009 (0.028)***	0.01892 (0.056)***
RGGI - China Guangdong	-0.005597 (0.04)***	0.01848 (0.03)***	-0.04602 (0.237)***	1.004 (0.027)***	-0.008462 (0.053)***
RGGI - China Hubei	-0.001311 (0.04)***	-0.00362 (0.035)***	-0.05518 (0)***	1.006 (0.026)***	-0.01219(0.05)***
Quebec - South Korea	0.01849 (0.03)***	-0.001396 (0.033)***	0.1084 (0.176)***	1.012 (0.018)***	0.02384 (0.037)***
Quebec - China Shenzhen	-0.003571 (0.03)***	-0.00362 (0.035)***	-0.03147 (0.191)***	1.004 (0.019)***	-0.00723 (0.037)***
Quebec - China Guangdong	-0.0012 (0.03)***	-0.001396 (0.033)***	-0.001094 (0.173)***	1.01 (0.017)***	0.0009459 (0.044)***
Quebec Argus - China Hubei	0.01628 (0.03)***	0.01608 (0.03)***	0.0126 (0.168)***	1.002 (0.018)***	0.02078 (0.032)***
South Korea - China Shenzhen	-0.02361 (0.03)***	-0.02435 (0.031)***	-0.1673 (0.179)***	1.019 (0.021)***	0.004771 (0.027)***
South Korea - China Guangdong	0.01611 (0.03)***	0.01598 (0.033)***	0.04178 (0.188)***	1.005 (0.02)***	0.02615 (0.036)***
South Korea - China Hubei	0.07537 (0.03)***	0.07399 (0.03)***	0.4302 (0.167)***	1.046 (0.018)***	0.09818 (0.043)***

This table presents the results of the correlation of the estimates of the dependence of the different exchanges for spot contracts by pair of exchange. We incorporated five copula functions (normal, Student-t, Frank, Gumbel and Clayton) in order to estimate the dependence parameters θ for the sample.

2.5.2 Best Copula Model

To determine which copula yielded the best results, we employed the goodness-of-fit test, which compares the distance between the estimated and empirical copulas. The larger the value of the statistics are, the higher the probability that the null hypothesis that copula C belongs to class C_0 is rejected. Kojadinovic et al. (2010) proposed a multiplier approach to find the p-values related to the test statistics, overcoming the problem of dependence of the unknown parameter θ when estimating the distribution. Greater p-values indicate that the distance between the estimated and empirical copulas is smaller, suggesting that the copula under examination best fits the data.

The results of the goodness-of-fit tests and tail dependence are summarized in Tables 2.7 and 2.8. We found that the magnitudes of the tail dependencies in either direction varied significantly across the carbon market pairs. This suggested that the strength of market linkages under extreme conditions were quite different among the pairs.

For the EU and California carbon markets, the Frank copula provided the best fit. The symmetric relationship indicated that the carbon markets moved in the same direction. For the EU and RGGI, the asymmetric copulas (Gumbel and Clayton) provided the best fit, suggesting asymmetric comovements in the carbon allowance prices. However, the tail dependence between the two carbon markets was very low. For California and RGGI, the Normal and Gumbel copulas provided the best fit. The tail dependence was very low in this case.

The goodness-of-fit tests for spot returns indicated the presence of asymmetry since most of the pairs were best fitted by the Frank, Gumbel and Clayton copulas. The EU tail dependence with the Asian carbon markets was higher than that with the North American carbon markets. The EUA had a zero-tail dependence on the California, RGGI and Quebec carbon markets. The North American carbon markets also registered higher tail dependence with the Asian carbon markets. The strongest tail dependence was noted for the California and Quebec carbon markets, which might be due to their existing link. The Californian and RGGI tail dependence was almost zero for both future and spot prices.

Table 2.7: Results for the Goodness-of-Fit-Tests and Tail Dependence Coefficients of the Best Copulas (Future)

Exchanges	Normal	student's t	Frank	Gumbel	Clayton	Lower Tail	Upper Tail
EUA - California	0.866	0.658	**0.802**	0.71	0.781	0	0.011
EUA - RGGI	0.688	0.0195	0.69	**0.748**	0.649	0	0.00689
California - RGGI	0.0405	0.0045	0.0215	**0.1**	0.0594	0	0.0177

This table presents the results of the goodness-of-fit-tests and tail dependence coefficients of the best copulas, for the different exchanges, for future contracts by pair of exchange. We incorporated the five copula functions (normal, Student-t, Frank, Gumbel and Clayton) and add information about lower tail and upper tail values.

Table 2.8: Results for the Goodness-of-Fit-Tests and Tail Dependence Coefficients of the Best Copulas (Spot).

Exchanges	Normal	student's t	Frank	Gumbel	Clayton	Lower Tail	Upper Tail
EU - California	**0.308**	0.0195	0.172	0.228	0.242	0	0
EU - RGGI	0.0944	0.167	0.284	0.0135	**0.294**	0	0
EU - Quebec	0.0574	5.00E-04	0.0215	0.153	**0.167**	0.000273851	0
EU - South Korea	0.168	0.112	0.103	**0.257**	0.137	0	0
EU - China Shenzhen	00.0684	0.0804	0.0465	**0.107**	0.0984	0	0.03869
EU- China Guangdong	**0.0984**	5.00E-04	0.0495	0.0335	0.0614	0	0
EU - China Hubei	0.0924	0.0504	0.0594	**0.147**	0.124	0	0.01232721
California - RGGI	**0.44**	0.206	0.374	0.0634	0.41	0	0
California - Quebec	0.257	**0.777**	0.282	0.423	0.0864	0.1041575	0.1041575
California - South Korea	0.0564	0.101	0.0425	**0.186**	0.0704	0	0.01232721
California - China Shenzhen	0.237	0.151	**0.295**	0.0864	0.271	0	0
California - China Guangdong	0.239	0.155	0.171	**0.482**	0.177	0	0.02831111
California - China Hubei	0.73	0.00549	0.588	0.113	**0.603**	3.09E-20	0
RGGI - Quebec	0.881	0.477	0.063	0.31	**0.892**	0	0
RGGI - South Korea	0.105	0.187	0.112	**0.82**	0.0233	0	0.00825109
RGGI - China Shenzhen	0.181	0.362	0.469	**0.875**	0.458	0	0.01232721
RGGI - China Guangdong	**0.117**	0.0265	0.0704	0.0874	0.0984	0	0
RGGI - China Hubei	**0.565**	0.0435	0.493	0.544	0.509	0	0
Quebec - South Korea	**0.473**	0.0025	0.375	0.151	0.46	0	0
Quebec - China Shenzhen	0.414	5.00E-04	0.33	**0.485**	0.398	0	0.005515466
Quebec - China Guangdong	0.0425	0.294	0.0135	**0.325**	0.0335	0	0.0136787
Quebec - China Hubei	0.342	0.0125	0.401	0.422	**0.48**	3.26E-15	0
South Korea - China Shenzhen	**0.191**	0.0784	0.186	0.0984	0.156	0	0
South Korea - China Guangdong	0.131	0.0015	0.0844	**0.53**	0.144	0	0.006885108
South Korea - China Hubei	**0.428**	0.291	0.313	0.268	0.109	0	0

This table presents the results of the goodness-of-fit-tests and tail dependence coefficients of the best copulas, for the different exchanges, for spot contracts by pair of exchange. We incorporated the five copula functions (normal, Student-t, Frank, Gumbel and Clayton) and add information about lower tail and upper tail values.

2.5.3 Discussion

This study shed light on the very important topic of the dependence structure among the different carbon markets. The results clearly highlighted some dependencies, usually at the regional level. This study naturally led to a set of policy recommendations.

If the ultimate goal is truly to have a unique price for carbon emissions throughout the world (see Green et al. (2014)) to reflect its true environmental cost, policy makers cannot ignore the regional dependencies. On the one hand, strengthening them can foster the creation of larger carbon clubs that, in turn, could ultimately lead to a unique global market. On the other hand, some local challenges might be preferred above the greater good of a global market. Whether regional carbon clubs should be encouraged remains an open question. In a similar vein, the regional dependence in this study rested on the existing regional networks, i.e., the North American and EU being regional initiatives. Policy makers should pay attention to upcoming carbon markets from emerging countries (such as Ghana, Jordan, Singapore, Vanatu and more) and determine if they are able to converge on a regional level with a similar effectiveness. In this race of converging to the global carbon market, the regional clubs constructed by emerging markets will need to be on a larger scale and will demand more linkages with other regional clubs to ensure liquidity and trading in the market.

This study also raised another interesting point associated with the advent of new carbon markets and the upcoming implementation of Article 6 of the Paris Agreement. With the mushrooming of regional initiatives, paying the (high) cost of carbon contracts is almost unavoidable, which encourages carbon leakage. Strong regulation should be put in place to legally enforce price targets across different markets to ultimately make the prices converge on the different

ETSs. Moreover, the transfer of emission reductions from the Global South to the Global North shall entail an empowerment of dominant countries and elite groups vis-a-vis subordinates across the globe and an exacerbation of global inequities. Recommendations to strengthen the digital infrastructure as well as the monitoring, reporting and verification processes are prominent.

We also highlighted the interesting fact that newly created schemes tended to be positively linked to the EU ETS, emphasizing the real pioneering role of the EU ETS. One of the solutions for reaching a global market might be the extension of the EU ETS, strengthening its position, which in turn could affect all the new initiatives by installing a natural price correlation between the ETSs. The EU ETS has already started to follow that strategy by encompassing the Swiss ETS, but it may enlarge even more, notably through West Asian ETSs, to eventually make a bridge with Chinese pilot markets. Nevertheless, during the integration of emerging carbon markets with the EU ETS, policy makers should not repeat the CDM process (whereby developing countries were providing the carbon credits) which eventually became irrelevant and had to be cancelled.

Since the compliance markets are very much in the limelight, policy makers should not ignore the presence and impact of voluntary carbon markets on carbon prices. The nexus between compliance and voluntary carbon markets has not yet received the scientific attention it deserves, mainly due to the lack of data and transparency regarding counter trading in voluntary carbon markets. With the implementation of Article 6 of the Paris Agreement, the transfer of international carbon emissions will influence the carbon markets and ultimately price dynamics.

2.6 Concluding Remarks

Tail dependence characterizes the linkages of cross carbon markets and is of interest to investors as an economic barometer in carbon financing. The study of the dependence structure of carbon markets is also crucial for designing a unique global carbon market to reach global climate goals. However, the literature regarding the dependence structure of multiple carbon markets is limited. We aimed to shed light on the dependence structure of carbon markets through GARCH-copula models, which have been extensively adopted in the literature.

We used three carbon markets for the future price analysis: EU, RGGI and California. We expanded the sample to include EU, RGGI, California, Quebec, South Korea and three Chinese carbon markets to measure the dependence of spot prices. By implementing the copula model to assess the dependence structure among these carbon markets, we found that there was more asymmetric dependence among carbon markets in the spot returns. The EU ETS, one of the largest carbon markets in the world, exhibited very low and negative dependence on both the oldest carbon markets, RGGI, California and Quebec, and on the upcoming markets in Asia (South Korea and Chinese carbon markets). The RGGI, California and Quebec carbon markets are also more likely depend on each other, and similar results have been obtained for Asian carbon markets. This suggests a greater potential for regional carbon clubs rather than an expanding global carbon market.

This study suggests avenues for future research. More platforms and a longer time period can be investigated, both for spot and future contracts, notably on the most recent eastern carbon markets. Another avenue of research could involve the use of tail dependence to design a unique carbon market or to reduce carbon leakage. In addition, the regime switching model can be implemented to measure the multivariate dependence structure of carbon markets.

Chapter 3

Carbon Pricing and News Announcements

Article title: Simultaneous Impact of News Announcements on Global Carbon Prices

Abstract: Understanding how international climate-related news shapes the price dynamics in these markets is important for market participants. Compared to existing studies that focus on a single category of news from market-based regulations, this paper contributes to the literature by investigating the extent to which announcements from diverse stakeholders can impact carbon prices. We examine the effect of 7 news categories encompassing international announcements on prices in eight carbon markets around the world by running an event study on daily stock returns for spot contracts from 20 January 2015 to 30 June 2020. The results demonstrate that news announcements affect carbon prices and the magnitude of the market reaction is a function of the type of news. Positive news appears to have a longer effect than negative news. Similarly, the news categories tend to influence carbon markets differently. Carbon markets react more to market reforms than to other announcements such as controversies, lobbying or the Paris Agreement.

Keywords: carbon markets, carbon pricing, event study, announcements, news sentiment

JEL: G1, G14, Q02, Q5

3.1 Introduction

The last decade has witnessed a wave of carbon markets being established worldwide (Ramstein et al., 2020). With several significant carbon price dynamics, notably prices skyrocketing in the EU ETS, President's Biden election with an ambitious agenda for climate policy and China's commitment to carbon net zero by 2060, carbon markets will play a pivotal role in achieving climate targets. As carbon markets are growing as a dominant response policy, their role at the international level, in particular with respect to Article 6 of the Paris Agreement, appears promising. Given this exploratory development, carbon markets are evolving into an important financial market (Zhu et al., 2019b). They are considered a cost-effective policy instrument to reduce greenhouse gas emissions. Unlike other naturally formed markets (e.g., the oil market), the carbon market has been regarded as policy-oriented in each existing emission trading scheme (ETS) around the world (Song et al., 2019). This government-led mechanism is likely to be influenced by an array of supervisory systems, trading rules, international climate agreements and spillovers from peer carbon markets (Newell et al., 2014). This very trait of carbon markets makes them vulnerable to shocks from vital information announcements or regulatory modifications.

The release of new information on carbon markets is sporadic and frequent. As countries and regions are globally implementing new carbon policies, the influence that these policies will have on the competitiveness, productivity and pricing of carbon emission permits had attracted the attention of academic research. The impact of events or news on carbon markets have been regularly investigated in several academic papers. Miclaus et al. (2008) study the announcement related to Phases I and II of National Allocation Plans (NAPs) on the EU ETS and report no evidence of cumulative abnormal returns. Mansanet-

Bataller and Pardo (2009) test the same set of announcements and document significant market reactions before and after the events. Lepone et al. (2011) highlight the level of informational asymmetry and data leakage observed in the carbon market. They report cumulative abnormal returns associated with these types of institutional announcements. Chevallier et al. (2009) reports a considerable impact of the European Commission's disclosures on carbon price formation. More recently, Sanin et al. (2015) suggests that media news can lead to a time-varying price jump in carbon prices for the EU ETS.

The aim of this paper is to study the impact of new information at the international level on carbon prices and their volatility. To the best of our knowledge, this is the first attempt to study this issue across different carbon markets around the world. Thus far, the effect of news across carbon markets has remained restricted to a single carbon market. Similarly, the type of news has been limited to a set of supply-related announcements, such as NAPs or annual releases of verified emissions data. In addition to these news announcements, this paper also investigates demand-side announcements such as linkages amongst carbon markets, lobbying and controversies over carbon pricing, policy makers' ambitions and the introduction of new compliance carbon markets as well as the United Nations' Conference of Parties and, specifically, the Paris Agreement. We thoroughly investigate how carbon prices react to related news announcements to empirically study information processing across eight carbon markets: the EU ETS, California, RGGI, Quebec, South Korea and three Chinese ETS namely Guangdong, Hubei and Shenzhen. Specifically, the study analyses whether (i) news announcements on carbon markets affect the value of carbon prices in emission trading systems; (ii) there is a difference among the types of news announcements with respect to their effect on the value of carbon prices in emission trading systems; and (iii) there is a difference in the market reaction before and after news announcements. Using news derived from Bloomberg's carbon markets news section and an event study methodology (ESM), our results reveal that news announcements influence carbon prices and the magnitude of the reaction differs depending on the type of news. Positive news appears to have a longer effect than negative news. Similarly, the categories of news tend to influence the carbon markets differently. Market reforms significantly impact carbon markets relative to other third-party announcements, such as controversies and lobbying. The oldest ETSs, i.e., EU and RGGI, are more impacted by the announcements than the more recently created ETSs. Finally, announcements tend to have an immediate impact on carbon markets rather than a post-event effect or there being an anticipation of such news.

The remainder of the paper is structured as follows. The next section describes in detail the types of announcements that have been considered, how the release of information is produced and when it should arrive in the market. The data and methodology are explained in Section 3. The fourth section details the empirical results, and the final section concludes the paper.

3.2 Background

3.2.1 Information Processing in Carbon Markets

The empirical literature on carbon pricing mechanisms has been geared towards economic activities and the relationship between energy prices (Chevallier, 2009; Gronwald et al., 2011b; Hammoudeh et al., 2014; Sousa et al., 2014; Tan and Wang, 2017b). Several elements further highlight the importance of carbon market sentiment, showing that carbon prices in the EU ETS fell by nearly half their value following the publication of the first carbon verification report

(Marcu et al., 2017; Ellerman and Buchner, 2008). Jia et al. (2016) showcase that verified emission announcements, released annually for the period 2006-2013, cause shocks and increase risk of information leakage on the road to price discovery. Quantifying sentiment indicators has remained controversial in previous studies.

Existing studies related to carbon markets adopt market activity indicators to represent sentiment. Koch et al. (2014) and Jiao et al. (2018) study macroeconomic sentiment indicators to explain the changes in EU ETS prices. Reboredo (2014) suggests that macroeconomic and financial variables influence oil prices which transcends to carbon markets. Zhu et al. (2018) develop a multi-scale event analysis through ensemble empirical mode decomposition (EEMD) to gauge the impact of economic crises in the EU ETS.

Additional studies have argued that regulatory changes and policy decisions are likely to affect emission allowance prices (Daskalakis and Markellos, 2009; Koch et al., 2014; Kossoy and Guigon, 2012). Conrad et al. (2012) find that NAPs affect price sensitivity during the 2006 and 2007 emission announcements. Ye and Xue (2021) employ a carbon tone index of news on the EU ETS through the latent Dirichlet allocation method. Deeney et al. (2016) use the event study and GARCH volatility methods to assess the impact of EU Parliament decisions on EU ETS prices. Mansanet-Bataller and Pardo (2009) analyse 70 regulatory news announcements on carbon prices for the period 2004 to 2007 using the event study method by Mckenzie et al. (2004). The impact of trading policy on the Chinese Pilot Shanghai Emission Allowance price was analysed through the Mean Reversion Test, the Cox-Ingersoll-Ross (CIR) model and the event study method (Song et al., 2018). The findings show that trading policy affects emission allowance prices through the fundamentals of supply and demand. Hintermann (2010) and Rezaee et al. (2017) find that trading policy can result in structural breaks in carbon prices during the first phase of the

EU ETS. Blyth et al. (2007) view changes in climate policy as an important external factor that affects carbon price evolution. On the basis of this, Blyth et al. (2009) develop a framework to identify what policy can markedly influence carbon prices. Alberola et al. (2007) and Alberola et al. (2008) state that policy is a major price discovery determinant in early phases of the EU ETS. More recently, Yang et al. (2018), Song et al. (2019) and Lu et al. (2021) further investigate the relationship between policy and carbon price evolution in the Chinese pilot markets.

News related to energy markets is also strongly related to carbon price movements. Chevallier (2010) study the impact of Australian ETS news on wholesale electricity spot prices using an ARMA(1,1)-GARCH(1,1) model and report that ETS news tends to increase the levels and volatility of electricity spot prices. Zhang and Sun (2016) assess the asymmetric shocks of positive and negative information on carbon and energy markets through the use of the DCC-GARCH method. Fan and Todorova (2017) further investigate the Chinese pilot ETSs and the overall sentiment of the CHVIX and OVX Chinese markets alongside energy prices.

Previous studies focus primarily on the appraisal of the EU ETS and only a single type of news. They lack a systematic review of how changes in the international arena can impact carbon markets and emission allowance prices. By extending the categories of news beyond market policies and across eight carbon markets, this paper significantly contributes to the literature and elaborates further on how market players perceive news.

3.2.2 Types of News Announcements related to Carbon Markets

Controversies and Uncertainty Regarding Carbon Markets. There is an extended literature on the environmental integrity of international carbon markets, notably in the Kyoto Protocol context (Erickson et al., 2014; Cames et al., 2016a; Schneider and La Hoz Theuer, 2019; Greiner and Michaelowa, 2003; Spalding-Fecher et al., 2012). The issue of carbon leakage has also been flagged by existing studies (Calvin et al., 2015; Geres and Michaelowa, 2002; Kallbekken, 2007; Vöhringer et al., 2006). Based on IPCC (2014)'s report, the controversies over carbon markets are likely to arise from efforts at aggregate emission reduction over carbon trading. Hood et al. (2014) and Kreibich and Obergassel (2016) note the double counting of emission reductions in the Paris Agreement era. These news announcements highlight the uncertainty surrounding the carbon market's ability to reach a global consensus on Article 6 of the Paris Agreement and existing carbon markets' exposure to risks and challenges to achieving climate goals. Golub et al. (2017) state that the more uncertain policies affecting carbon markets are, the higher the cost of future emissions. Adekoya et al. (2021) also shed light on the fact that the EU ETS is a net receiver of shocks from other financial markets and policy uncertainty emerging from the US is a notable driver of this interconnectedness. These findings are reinforced by Ye et al. (2021), who confirm a cross-correlation behaviour structure in the EU ETS and economic policy uncertainty specifically from the UK and the US.

Lobbying by Stakeholders of Carbon Markets. Since the implementation of the first emission trading system, diverse stakeholders have been lobbying for its effectiveness (Jevnaker and Wettestad, 2017). Over the years, the performance of carbon markets has been criticised due, notably, to the drop in emission allowance prices, the oversupply of allowances and carbon leakage (Wettestad and Jevnaker, 2016). This has led to the emergence of lobbying coalitions that are a function of multiple factors such as policy problems and the availability of resources (Holyoke, 2009). Carbon markets have also been subject to lobbying coalitions mainly encompassing non-governmental organisations (NGOs) that have been vocal about the weaknesses in the system (Meckling, 2011). Second, corporations have also been at the forefront of lobbying on related matters. The weak official oversight of most carbon markets has also opened the door to fraudulent activity by private actors. To preserve the environmental integrity of carbon markets, the price of emission allowances should reflect the real cost of reducing what is considered a newly added and permanent ton of CO2 in the atmosphere. In turn, these behaviours are likely to influence the policy positions and market reforms, thereby impeding on pricing (Beyers and De Bruycker, 2018). Miard (2014) illustrates the different lobbying routes in the EU ETS. The work distinguishes between organisational forms of business interest representations ranging from individual firms lobbying directly via national associations or in alliance with other firms or groups. Rasmussen and Alexandrova (2012) analyses the EU membership's possible influence on actors' lobbying. To the best of our knowledge, no study has investigated the impact of lobbying on carbon prices.

Linking Carbon Markets. Linking carbon markets has also been at the centre of discussions since their emergence. Norway was linked to the EU ETS in 2009 as the first non-EU scheme. Australia and EU began considering the possibility of linking their carbon trading activities as early as 2018. Policy makers have also been advocating for a global carbon market as an outcome of the Paris Agreement (Beuermann et al., 2017; Bodansky et al., 2016; Ranson and Stavins, 2016; Schneider et al., 2017). Article 6.2 gives rise to the use of 'internationally transferred mitigation outcomes', while Article 6.4 establishes a new crediting mechanism subject to international oversight (Savaresi, 2016). Carbon market linkage can have both political and economic benefits. Politically, carbon market linkage will motivate regions to achieve more ambitious emission reduction targets. The literature and existing policies provide strong support for the linking of carbon markets. A report by the World Bank notes that a global carbon market could reduce global abatement costs by one-third in 2030 and by half in 2050 (Economics et al., 2016). Alexeeva and Anger (2016) studies the trade competitiveness and welfare impacts of linking carbon markets. The findings favour linking the EU ETS with other carbon markets, while the non-EU ETSs face a disadvantage in the form of competitiveness losses. Ma et al. (2019) appraises linkage among the China, Japan and South Korea ETSs and finds that such activities can boost the transaction scale and liquidity in all three countries.

Impact of Market Reform News on Carbon Markets. Market reforms can also induce shifts in stakeholders' sentiment and thereby affect trading activities. There is a rich literature on market reforms and their impact on carbon pricing, although they are restricted to a single market. Rezaee et al. (2017) find that market-related policy often causes excessive volatility in carbon prices. Hintermann (2010) states that such reforms have resulted in structural breaks in the EU ETS. The results have been confirmed for Chinese ETSs (Tan and Wang, 2017a). Excessive allowances can weaken reduction targets and eventually cause the prices to collapse (MacKenzie, 2009). Lepone et al. (2011) find that NAPs and verified emissions announcements have a significant impact on carbon returns but weaker impacts on carbon price volatility. Since the construction of carbon markets has mainly been based on a learning-by-doing process, the impact of such market reforms should be assessed (Chevallier et al., 2009; Fan et al., 2017).

New Carbon Market News. To date, to the best of our knowledge, no paper documents the impact of launching a new ETS on existing schemes. Amongst various greenhouse gas reduction practices, carbon markets are being favoured by many countries to meet the targets in the Paris Agreement. The World Bank report on State and Trends on Carbon Pricing 2020 stipulates that there are approximately 61 carbon taxes or emission trading systems in place or scheduled for implementation (World-Bank, 2020). China launched its national ETS in early 2021 but had been communicating frequently about it for the past five years. Over the last five years, at least thirteen countries publicised their plans for introducing a carbon market. In an era of increasing connectedness amongst carbon markets, there is a need to assess how market participants react to such announcements.

Paris Agreement and Carbon Markets. During the early UN climate negotiations, the scope of international investment in emission reduction projects was introduced in the form of the Kyoto Protocol, adopted in December 1997 (Jackson et al., 2001). In 2016, the Paris Agreement was ratified by 196 countries. The US announced its withdrawal from the Paris Agreement in June 2017, while China, the world's largest carbon emitter, was on the verge of launching its national ETS (Wang and Wang, 2017). Further hindsight about this international agreement has highlighted the concepts of international transfers, governance concerns, incentives and disincentives for raising ambition in carbon markets (Agreement, 2017; Cames et al., 2016b; Greiner et al., 2017; Klein et al., 2017; Howard et al., 2017).

Policy Makers' Ambition Regarding Carbon Markets. The reduction of GHG emissions has become a major concern for countries. Various measures have been taken worldwide to shift to a low-carbon economy (Stern and Stern, 2007). Policy makers have thus resorted to two promising carbon pricing mechanisms: carbon taxes and emission trading systems. Koch et al. (2016) investigate how the political process of making cap adjustments has shaped the market outcomes of the EU ETS. They find that there is a high market responsiveness to political events and reveal how participants view the evolution in the light of a particular announcement. Such evidence indicates that market participants are able to accurately price in new information provided by policy makers' decisions.

3.2.3 Methods for Sentiment Analysis of News

This section provides a review of the text sentiment analysis of news in financial markets. Loughran and McDonald (2016) reports that text can convey incremental information, thereby resulting in market predictability. Since the literature on news announcements regarding carbon markets is scarce, we resort to existing studies in energy and commodity markets. The similarity and spillover amongst energy, commodity and carbon markets have been widely studied which strengthens the viability of this reference.

Sentiment analysis is a growing area of research due to the sheer size of unstructured data that are now available. Two distinct types of sentiment analysis have been proposed: direct measures of sentiment through surveys and indirect measures through proxies or text mining (Chowdhury et al., 2014). This analysis has been further expanded into rule-based methods (relying on a small set of rules for short text sources), dictionary-based approaches (count the frequency of predefined positive and negative words), term-weighting approaches (use word frequencies from a training set to assign weight to each term) and machine-learning approaches.

Sinha (2016) find that the US stock market has under-reacted to the tone of news articles. Santi (2020) gather climate-related news from StockTwits from January 2010 to September 2019 to build a measure of investor climate sentiment. This sentiment is then regressed on carbon prices, oil prices and market portfolio performance. The study accounts for international events such as UN summits on climate change, global climate strikes and international environmental policies being implemented. Kuttner (2001) introduces a policy surprise measure to capture unexpected target rate changes in the market. The expected policy rate change is computed as the policy rate change minus the unexpected policy rate change. Belgacem et al. (2015) collect American economic announcements from Bloomberg to assess their effect on oil and stock markets. They separate the expected and unexpected component of the news through surprises as the difference between the real change in the indicator value from the market consensus forecast (Fleming and Remolona, 1997). López (2018) conduct a regression analysis on oil price indices based on dummy variables for ten news announcement items such as CPI, GDP, and Producer Price Index amongst others.

The sporadic growth of carbon markets around the world calls for assessments of the impact of related, international news on them. The EU ETS has been dominant and thrived as the largest carbon market for years. However, the noticeable performance of other carbon markets cannot be ignored. For instance, the Chinese pilot ETS has had an overall compliance ratio of over 99 percent and witnessed a trading volume exceeding 347 million tons of carbon dioxide equivalent at the end of 2019 (Lu et al., 2021).

In the present research paper, we attempt to significantly contribute to the literature by investigating the (to date and to the best of our knowledge) largest set of news categories and the highest number of ETSs. Most studies have solely focused on one type of news and a single market. Our study lifts the veil on the impact on news in carbon markets worldwide.

3.3 Data

Our dataset encompasses data from eight ETSs around the world: the EU ETS, California, Quebec, RGGI, South Korea, Shenzhen, Guangdong and Hubei. We use the EU ETS' EUA spot prices provided by the Intercontinental Exchange (ICE), Chinese Pilot and South Korean ETS prices provided by ICAP, RGGI and California ETS spot prices provided by Argus. Mizrach and Otsubo (2014) stipulate that the ICE ECX provides between 75 to 88 percent of price discovery for EU ETS trading. The seven Chinese pilot ETS are very recent, and data are not available for all of them. In this study, we therefore only include the Guangdong, Hubei and Shenzhen ETSs. Furthermore, throughout this analysis, we focus on carbon emissions' spot prices given that some carbon markets have yet to issue future contracts yet (e.g., Chinese pilot ETSs and South Korean ETS). As is traditional in the asset pricing literature, we use percentage return series rather than price series to overcome the problems of non-stationarity and high persistence in the price-series data.

Table 3.1 reports the descriptive statistics of carbon emissions' spot prices from these eight ETS.

Table 3.1: Descriptive Statistics of Carbon Prices

	EUA	California	Quebec	RGGI	South Korea	Shenzhen	Guangdong	Hubei
Mean	0.0008	0.0002	0.0001	0.0001	0.0007	0.0015	0.0006	0.0002
Median	0	0	0	0	0	-0.000005	0.0006	-0.0004
Maximum	0.1282	0.1036	0.1158	0.3322	0.0953	1.9637	0.4405	0.4124
Minimum	-0.1945	-0.1714	-0.1840	-0.3677	-0.1165	-1.7062	-0.4653	-0.4155
SD	0.02891	0.0083	0.0097	0.0207	0.0189	0.2415	0.0543	0.0414
Skewness	-0.3150	-6.1774	-4.6813	-1.4833	-1.1799	0.4103	-0.0375	0.1105
Kurtosis	4.3965	173.6253	122.3088	127.5131	16.4305	13.1370	15.9623	17.4204
Jarque Bera	1135.637***	1740985.656***	864643.0067***	934823.67***	15839.6414***	7990.6963***	11569.6667***	16424.1238***
Q	0.014826	0.014826	6.3623***	9.7216***	21.17***	249.96***	37.786***	89.007***

This table shows the descriptive statistics for each spot contract in our sample. The table depicts statistics on moments, median, maximum and minimum, as well as the test statistics associated with the Jarque-Bera and Ljung-Box Q tests.

We retrieve daily carbon market related news from the Bloomberg Environment and Carbon Market sections for the period ranging from January 2015 to June 2020. A total of 60,848 news headlines were screened (Table 3.2). The articles

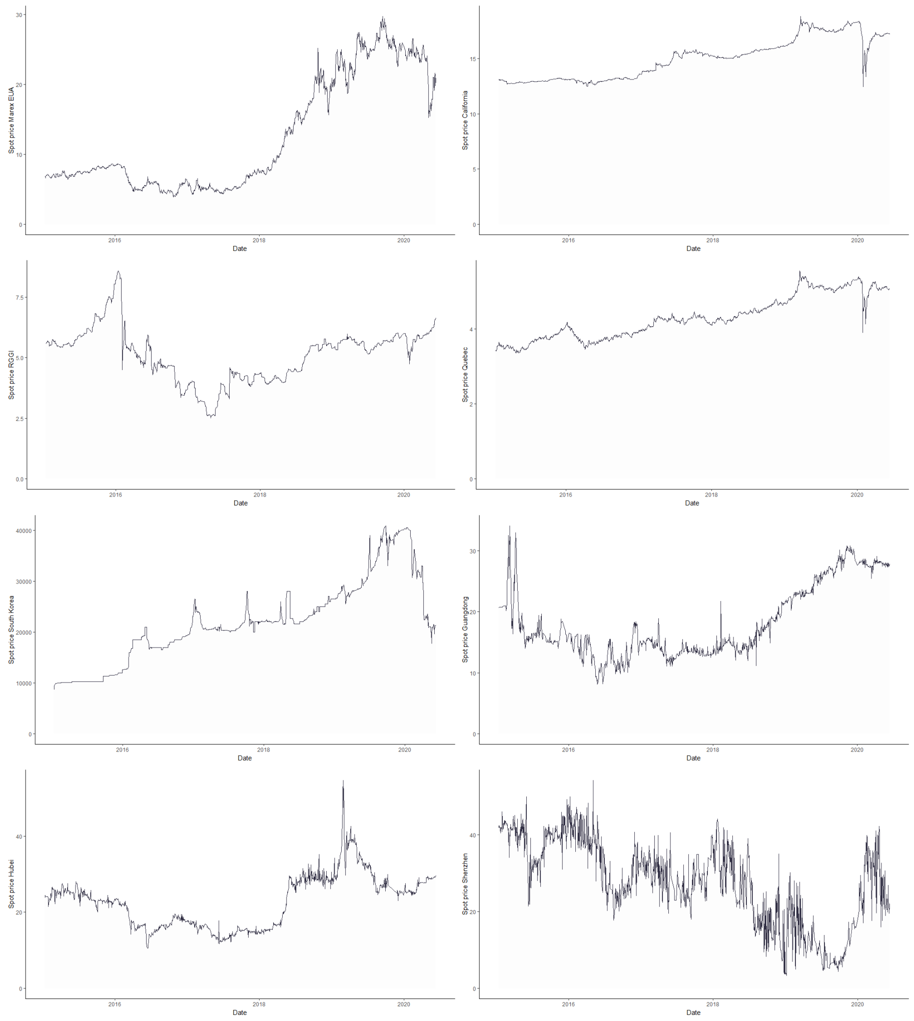

Figure 3.1: Daily Spot Prices of Carbon Allowances

The figures show the daily spot prices for EU, California, RGGI, Quebec, South Korea, Guandong, Hubei and Shenzhen, from left to right and top to bottom, respectively.

are provided by Bloomberg Intelligence, Carbon Pulse and other independent news reporters. Carbon Pulse provides in-depth news and intelligence about global carbon pricing schemes and climate change policies. Bloomberg conveys news about carbon markets and provides detailed coverage of related events. Bloomberg news is third-party content and, thus, does not originate from market participants themselves. Announcements from Bloomberg comprise novel information solely compared to other sources that tend to edit, perturb or shorten the content through editors. Overall, Bloomberg news provides the advantage of a more objective news source. Market participants usually receive the real-time message in the form of an email from Bloomberg. Instead of full news articles, we use headlines because they contain much less repetition and irrelevant words than the article itself (Nassirtoussi et al. (2015) and Li et al. (2021)).

Based on those headlines, the reports have been filtered such that only announcements focusing on carbon markets were extracted. A set of filter criteria were applied. First, we focus only on news written in English. Second, selected headings were carefully analysed to ensure the validity of the information. Third, special types of announcements such as alerts or personal opinions have been eliminated. Finally, news related to prices have been excluded to avoid simultaneity (Antonakis et al., 2010; Day, 2014).

For the purpose of this study, we rely on the package Sentimentr (Rinker, 2019) that has already been tested in energy and climate related studies, notably by Santi (2020) and Ikoro et al. (2018). The package allows us to accurately calculate text polarity sentiment. The use of valence shifters, negators, and amplifiers/deamplifiers ultimately helps to alter the impact of a polarised word. The sentiment value of each headline is calculated using the P/N ratio, which uses the number of positive and negative sentences obtained from the sentence polarity identification task. The sentiments perform well at detecting negative

Table 3.2: News Headlines Screened per Month

Month	2015	2016	2017	2018	2019	2020
January	389	436	469	475	504	735
February	722	648	748	585	820	872
March	918	752	953	882	976	1010
April	854	848	721	624	977	831
May	861	830	724	618	966	744
June	813	952	664	567	875	740
July	860	753	687	556	843	
August	640	751	508	633	793	
September	1035	735	534	688	890	
October	721	584	588	664	833	
November	923	721	793	744	793	
December	770	712	504	553	831	
Total number of news headlines	11521	10738	9910	9607	12120	6952

This table presents the distribution of the news analysed in this study per year (columns) and month (lines).

Table 3.3: News Headlines Related to Carbon Markets per Category

Category	**Total**
International Announcements	153
Controversies and Uncertainty	39
Linkage	18
Lobbying	20
Market Reforms	23
New Carbon Markets	13
Paris Agreement and Carbon Markets	26
Policy Makers' Ambition	14

This table lists the different news categories and the number of elements in each of them.

words but are less effective for positive and neutral words. As such, we analyse the polarity level from high-frequency words and amend the lexicons of those words in the package. Words such as 'backing', 'transparency', 'implement', 'pledge', 'commit', 'plan', 'add', 'install' and 'control' were then treated as positive rather than neutral. Finally, the number of news headlines per category is 52 for positive news, 55 for neutral news and 46 for bad news.

3.4 Methodology

We analyse the effect of announcements on carbon markets using an ESM as proposed by Fama et al. (1969) and Ball and Brown (2014). The ESM is a precise tool to identify the reaction of an asset's return series following an event. The approach is based on the fact that the effect of announcements is analysed during periods when news enters the market and avoids extended periods without announcements (Drake et al., 2011). In contrast with other methods, the ESM allows the researcher to focus on the occurrence of specific events that are isolated from other unwanted news disturbances that occur outside the event window (Fatum and M. Hutchison, 2003). The ESM has already been adopted in previous studies related to energy markets and energy-related news, e.g., Halova et al. (2014), Ji and Guo (2015), Chebbi (2018), Berk and Rauch (2016), and Capelle-Blancard and Petit (2019).

In this study, the event is a carbon-related news announcement, and the recorded date is the day on which the announcement is published on Bloomberg. The key element of an event study is the appropriate choice of estimation (pre-event) and event windows, and typically the estimation window and the event window do not overlap. It is customary to define an estimation window larger than the event window. The adoption of long event windows can violate the assumption of market efficiency (McWilliams and Siegel, 1997). Therefore, our event window is a five-day period: 2 days before the announcement, the day of the announcement and 2 days after the announcement. We carefully check the event windows in our analysis for contagion effects of several news items in the windows. When analysing the results, we carefully examine whether our results are driven by confounding events. As is standard in the ESM literature, we compute abnormal returns as the difference between actual returns and their expected values. Hence, for the i^{th} event at time t, the abnormal return AR_{it}

is defined as:

$$AR_{it} = r_{it} - E[r_{it}/X_{it}] \tag{3.1}$$

where, r_{it} denotes the actual return and $E[r_{it}/X_{it}]$ denotes the expected return, given the conditioning information X_{it} for the expected return model. We calculate expected returns from a model estimated on the basis of the returns before materialising the event window. All computations are based on log returns computed on close prices. When estimating the expected returns $E[r_{it}/X_{it}]$, we test the carbon prices' returns for auto-correlation and heteroscedasticity over all periods associated with the i^{th} event. As auto-correlation and heteroscedasticity are largely present in the returns, we employ an auto-regressive model. Hence, the expected returns are derived based on the following auto-regressive model:

$$r_{it} = \mu_i + \sum_{k=1}^{p} \beta_k R_{i,t-k} + \varepsilon_{it} \tag{3.2}$$

where μ_i is a constant and ε_{it} is an error term. It is estimated separately for each day t with an individual optimal lag length p determined with the Bayesian information criterion (BIC) (Schwarz, 1978). AR_{it} signals the informational content of the event on day t; if informative, it should significantly drive the price of allowances.

We then sum all the AR terms from $[T_1; T_2]$, i.e., the starting and ending days of the event window, to obtain the cumulative abnormal return CAR.

$$CAR_i(T_1; T_2) = \sum_{j=T_1}^{T_2} AR_{ij} \tag{3.3}$$

We then compute the cumulated average abnormal return $CAAR(T_1; T_2)$ by calculating the average of all $CAR_i(T_1; T_2)$:

$$CAAR(T_1;T_2) = \frac{1}{N}\sum_{i=1}^{N} CAR_i(T_1;T_2) \tag{3.4}$$

where N is the number of events. Finally, we test the hypothesis of whether $CAAR_i(T_1;T_2)$ is different from zero using the t-statistics:

$$t = \frac{CAAR(T_1,T_2)}{\sqrt{\frac{(T_2-T_1+1)\sum_{i=1}^{N}\hat{\sigma}_i^2}{N^2}}}\ N(0,1) \tag{3.5}$$

3.5 Results

Table 3.4 presents the impact of controversial and uncertainty news on CAAR. This type of news relates mostly to governing controversies over the effectiveness of carbon pricing, ambiguity over the host countries of carbon markets' ambitions to meet the Paris Agreement, carbon leakage highlights or countries raising concerns over the ETS mechanisms. The Chinese pilot markets seem to react almost instantly, while the effect is lagged by one day for the Californian and RGGI ETSs. The controversies do not seem to impact the EU ETS. The Quebec and South Korean ETSs seem to anticipate the news one day prior to the event, and the impact is felt two days post event. Previous studies by Golub et al. (2017) found that prices usually jump in a period of controversies and uncertainty. The oldest ETSs, EU, California and RGGI, are more resilient to such controversies than the more recent schemes in China. Additionally, controversies and uncertainty negatively affect carbon returns, which supports existing studies. The results are in line with Adedoyin and Zakari (2020), confirming that uncertainties decrease economic growth and consumption, thereby driving down CO2 emissions and prices.

Table 3.5 represents the linkage news' impact on CAAR. While some of the

Table 3.4: Controversial and Uncertainty News Impact on CAAR

Carbon market	-2	-1	0	1	2
California	0.050	0.014	-0.002	-0.093	-0.005
	(3.303)***	(1.113)	(-0.233)	(-5.33)***	(-0.246)
EUA	0.086	-0.021	0.001	-0.052	-0.001
	(1.558)	(-0.476)	(0.041)	(-0.814)	(-0.016)
RGGI	-0.095	-0.088	-0.001	-0.134	-0.012
	(-0.412)	(-2.766)***	(-0.026)	(-2.960)***	(-0.247)
Quebec	0.020	0.071	-0.001	-0.011	-0.099
	(1.049)	(4.538)***	(-0.049)	(-0.475)	(-4.009)***
South Korea	0.064	-0.088	-0.011	-0.287	-0.268
	(1.807)*	(-2.766)***	(-0.555)	(-0.142)	(-5.888)***
Guangdong	-0.067	0.072	-0.188	-0.084	0.171
	(-0.852)	(1.115)	(-4.126)***	(-0.920)	(1.671)*
Hubei	0.364	0.399	-0.188	-0.084	0.219
	(4.825)***	(6.482)***	(-4.126)***	(-0.920)	(2.247)***
Shenzhen	0.636	1.135	-0.562	0.090	0.433
	(1.651)*	(3.612)***	(-2.528)**	(0.202)	(0.872)

The figures represent the CAAR and the *t*-statistics are in brackets. The symbols *, ** and *** denote statistical significance at 10% , 5% and 1% levels respectively.

carbon markets are on the verge of linking their trading activities, this will have a ripple effect on the pricing. Linkage news relates to announcements of linkage discussions and when a linkage deal has been finalised. Most of the news articles include linkage between the EU ETS and other carbon markets. The findings show that such announcements have an immediate and post-effect in the EU ETS with high statistical significance along with a positive impact on CAAR. RGGI also registered high and significance reactions following linkage announcements; however, unlike EU ETS, a negative impact can be observed. The California and Quebec ETS are not affected by the linkage announcements despite their goals having been tied in 2016, which falls within the time period assessed. Compared to other ETSs, no news was related to South Korea forging linkages with other carbon markets, which in turn is reflected in the findings. There is no impact of such news on the event and post event-days. China has also been involved in diplomatic discussions to link their ETSs, and these translated into a significant impact on the announcement day for Guangdong and Hubei. The findings conform with those of Alexeeva and Anger (2016), who find that linkage eventually leads to a disadvantage for non-EU ETSs. With the advent of Article 6 of the Paris Agreement, which was finalised in COP26 in late 2021, this effect of linkage can influence carbon pricing differently in the near future. The working programme to transfer international mitigation outcomes is only now being developed. Therefore, we can expect further conversations on linking carbon markets to emerge and eventually influence their mechanisms and pricing.

Carbon markets have often been considered fertile grounds for lobbying by various stakeholders. Corporations can spend significant resources to influence carbon market mechanisms (Grey, 2018). Table 3.6 represents the impact of lobbying on CAAR. The news items relate to stakeholders such as non-governmental organisations and companies lobbying for effective carbon pricing and to expand the ambition of carbon markets. Most announcements in this category are related to the EU ETS. A significant impact has been registered in the EU and RGGI, the oldest ETSs. Such lobbying in the European or US arena influences the Chinese ETSs but not others. China, with its ambitious carbon policy design, has always been considered a direct threat to the early and preeminent position of the EU ETS, and as such, lobbying news might be taken into consideration in those markets. Our findings contribute to the existing literature because there is no previous study that quantifies the impact of lobbying news on carbon prices. It can be deduced that impeding lobbying leads to increased carbon prices in the EU and Shenzhen ETSs while RGGI

Table 3.5: Linkage News Impact on CAAR

Carbon market	-2	-1	0	1	2
California	-0.005	-0.009	-0.016	-0.007	-0.003
	(-0.302)	(-0.694)	(-1.829)*	(-0.382)	(-0.158)
EUA	0.157	-0.119	-0.098	0.229	-0.127
	(2.861)***	(-2.649)***	(-3.068)***	(3.603)***	(-1.786)*
RGGI	-0.008	0.000	0.344	-0.159	-0.142
	(-0.206)	(-0.014)	(15.245)***	-(3.528)***	(-2.814)***
Quebec	-0.030	-0.029	-0.007	-0.001	-0.006
	(-1.552)	(-1.867)*	(-0.604)	(-0.038)	(-0.241)
South Korea	0.123	-0.089	-0.008	-0.039	-0.035
	(3.491)***	(-3.073)***	(-0.395)	(-0.964)	(-0.767)
Guangdong	-0.050	0.154	-0.219	-0.226	-0.019
	(-0.637)	(2.392)**	(-4.794)***	(-2.480)**	(-0.184)
Hubei	0.054	-0.081	-0.158	0.315	0.180
	(0.722)	(-1.310)	(-3.629)***	(3.621)***	(1.845)*
Shenzhen	0.069	0.370	-0.336	0.161	-0.224
	(0.180)	(1.177)	(-1.510)	(0.362)	(-0.450)

The figures represent the CAAR, and the t-statistics are in brackets. The symbols *, ** and *** denote statistical significance at 10% , 5% and 1% levels respectively.

and Hubei registered a negative relationship.

In addition, Table 3.7 shows that market reforms have an immediate impact on the announcement day in all carbon markets. The findings are entirely consistent with MacKenzie (2009), Lepone et al. (2011), Fan and Todorova (2017) andTan and Wang (2017b). It can also be deduced that such announcements are foreseen by the market and, as such, information disclosure should already have taken place in such cases. No post-announcement impact is registered from market reforms communications. Ren and Zhu (2020), who study the announcement of market reforms in Chinese carbon markets, find that the effect lasts 43 days prior to the announcements and disappears 13 days after

Table 3.6: Lobbying News Impact on CAAR

Carbon market	-2	-1	0	1	2
California	-0.003	0.002	-0.011	-0.015	-0.007
	(-0.185)	(0.137)	(-1.239)	(-0.840)	(-0.366)
EUA	0.056	0.107	0.133	0.208	0.213
	(1.014)	(2.372)*	(4.200)***	(3.272)***	(3.003)***
RGGI	0.043	-0.024	-0.141	-0.241	-0.285
	(1.089)	(-0.748)	(-6.222)***	(-5.343)***	(-5.641)***
Quebec	0.004	-0.001	0.017	0.020	0.008
	(0.220)	(-0.061)	(1.524)	(0.922)	(0.337)
South Korea	0.077	0.050	-0.008	0.051	0.057
	(2.181)***	(1.720)*	(-0.378)	(1.249)	(1.260)
Guangdong	-0.177	-0.013	-0.111	-0.125	-0.136
	(-2.241)**	(-0.201)	(-2.432)	(-1.365)	(-1.328)
Hubei	0.085	-0.114	-0.478	-0.488	-0.274
	(1.121)	(-1.855)*	(-10.968)***	(-5.598)***	(-2.811)***
Shenzhen	1.268	0.131	1.351	0.464	0.098
	(3.294)***	(0.416)	(6.080)***	(1.043)	(0.198)

The figures represent the CAAR, and the t-statistics are in brackets. The symbols *, ** and *** denote statistical significance at 10% , 5% and 1% levels respectively.

them. The latter also confirms that compared to the impacts in the previous compliance periods, the impacts in the latter two periods were stronger and shorter-lived. Similarly, the findings show that market reform announcement impacts are short lived. Unlike the other ETSs, the EU ETS registered a negative impact from market reforms. This can be related to the intense discussions and negotiations on market reforms by a large number of countries regarding the EU ETS compared to other ETSs that are mostly nationally governed and regulated with less intervention from stakeholders.

There are around 13 announcements related to the introduction of carbon markets in the past five years. The new carbon markets stem from diverse regions

Table 3.7: Market Reform News Impact on CAAR

Carbon market	-2	-1	0	1	2
California	-0.092	-0.228	0.195	0.078	0.102
	(-6.143)***	(-18.514)***	(22.428)***	(0.000)	(0.000)
EUA	-0.242	-0.330	-0.079	-0.768	-0.633
	(-4.398)***	(-7.347)***	(-2.490)**	(-0.012)	(-0.009)
RGGI	-0.150	-0.116	0.128	0.089	0.264
	(-3.825)***	(-3.624)***	(5.665)***	(0.001)	(0.003)
Quebec	-0.097	-0.275	0.203	-0.022	-0.043
	(-5.045)***	(-17.580)***	(18.349)***	(0.000)	(0.000)
South Korea	-0.093	-0.257	-0.158	-0.238	-0.226
	(-2.637)***	(-8.916)***	(-7.733)***	(-0.002)	(-0.002)
Guangdong	0.014	0.272	0.121	0.340	0.257
	(0.173)	(4.214)***	(2.651)***	(0.008)	(0.005)
Hubei	-0.087	-0.089	0.213	0.081	0.167
	(-1.147)	(-1.443)	(4.884)***	(0.002)	(0.003)
Shenzhen	0.058	-0.297	0.608	0.179	-0.550
	(0.150)	(-0.945)	(2.736)***	(0.020)	(-0.055)

The figures represent the CAAR, and the *t*-statistics are in brackets. The symbols *, ** and *** denote statistical significance at 10% , 5% and 1% levels respectively.

such as Kenya, Mexico, India, Nova Scotia and Indonesia. The aviation carbon offsetting program has also been prominent, as have the voluntary carbon markets of indigenous groups. The introduction of new carbon markets has an immediate impact on the oldest ETSs such as the EU, California, Quebec and RGGI, while the most recent ETSs, mainly from Asia, are not impacted. South Korea, Guangdong and Hubei registered a significant impact prior to and after the announcement. RGGI anticipates such news compared to EU and California, which only experience an impact on the event day. The EU ETS and Quebec registered a negative impact from new carbon markets compared to RGGI and California, which experience a positive impact. This disparity can also be due to an existing and foreseen linkage between carbon markets. The EU ETS is one step ahead in linking with other carbon markets such as in Norway, Switzerland and Australia compared to other carbon markets. Thus, market participants are likely to exploit the introduction of new carbon markets, as it can ultimately influence trading through linkages.

Table 3.8: New Market News Impact on CAAR

Carbon market	-2	-1	0	1	2
California	-0.005	-0.004	0.020	0.024	0.038
	(-0.333)	(-0.339)	(2.302)**	(1.389)	(1.955)*
EUA	-0.024	0.002	-0.152	0.031	0.087
	(-0.428)	(0.049)	(-4.797)***	(0.485)	(1.231)
RGGI	-0.220	-0.488	0.260	-0.182	0.004
	(-5.625)***	(-15.286)***	(11.505)***	(-4.036)***	(0.071)
Quebec	-0.004	0.011	-0.021	-0.013	0.008
	(-0.220)	(0.674)	(-1.900)*	(-0.570)	(0.312)
South Korea	0.091	0.157	-0.021	0.165	0.099
	(2.575)***	(5.441)***	(-1.006)	(4.060)***	(2.164)
Guangdong	0.093	0.188	-0.053	0.284	0.307
	(1.176)*	(2.913)***	(-1.158)	(3.115)***	(3.011)***
Hubei	-0.588	-0.579	-0.052	-0.579	-0.523
	(-7.790)***	(-9.404)***	(-1.188)	(-6.644)***	(-5.369)***
Shenzhen	0.300	-0.174	-0.180	-0.168	-0.198
	(0.780)	(-0.554)	(-0.810)	(-0.377)	(-0.398)

The figures represent the CAAR, and the t-statistics are in brackets. The symbols *, ** and *** denote statistical significance at 10% , 5% and 1% levels respectively.

The existing literature has shed light on the influence of politics on carbon markets, especially since governments play a crucial role in their design. News related to policy makers ambitions' relates to the governments' climate mandate and especially how they increase their targets. These news articles have been restricted to countries that already have a carbon market established or scheduled. Table 3.9 shows the results. In the EU ETS, the policy makers' ambitions are influential since an immediate effect is noted. Similarly, the Chinese ETS records a significant impact of policy makers' ambitions. On the contrary, RGGI and California do not seem to be impacted by such news. This might be due to the uncertainty prevalent in government targets. For example, the US withdrew from the Paris Agreement just four days after it entered into force in November 2016. The US also exited the Kyoto Protocol in 2001. Despite the resistance to commit to international agreements, the US has adopted carbon pricing mechanisms and policy makers' ambitions do not seem to influence these markets' trading activities.

Table 3.9: Policy Makers Ambitions' Impact on CAAR

Carbon market	-2	-1	0	1	2
California	0.020	0.020	0.006	-0.002	-0.009
	(1.322)	(1.645)*	(0.702)	(-0.109)	(-0.482)
EUA	-0.067	-0.110	-0.070	-0.318	-0.230
	(-1.225)	(-2.452)**	(-2.202)**	(-5.002)***	(-3.235)***
RGGI	-0.029	-0.015	-0.006	0.024	0.023
	(-0.748)	(-0.475)	(-0.251)	(0.540)	(0.450)
Quebec	0.015	0.035	0.015	0.018	0.009
	(0.783)	(2.268)**	(1.350)	(0.826)	(0.365)
South Korea	0.076	0.131	0.011	-0.038	0.007
	(2.152)**	(4.553)***	(0.544)	(-0.932)	(0.163)
Guangdong	0.018	0.060	0.153	0.239	0.387
	(0.228)	(0.930)	(3.359)***	(2.620)***	(3.790)***
Hubei	0.165	0.149	0.075	0.074	-0.065
	(2.189)**	(2.421)**	(1.730)*	(0.851)	(-0.664)
Shenzhen	-0.369	-0.741	-1.054	-1.255	-1.997
	(-0.958)	(-2.356)**	(-4.744)***	(-2.824)***	(-4.019)***

The figures represent the CAAR, and the t-statistics are in brackets. The symbols *, ** and *** denote statistical significance at 10% , 5% and 1% levels respectively.

The Paris Agreement ratified during COP21 was in the headlines for the period assessed from 2015 to 2020, mostly due to recurrent negotiations in every COP since 2015. This has several implications for the carbon market environment such as Article 6 dealing with the international transfer of mitigation outcomes, discussions of a global carbon market or even market clubs. News related to the Paris Agreement significantly impacts most carbon markets except for Guangdong and Shenzhen (Table 3.10. The EU ETS registers the highest positive impact on its CAAR. Conversely, the California and Quebec ETSs register a strong negative effect in their CAARs, while RGGI displays a minor positive impact. South Korea seems to be significantly impacted in the pre- and post-announcement periods.

Table 3.10: Paris Agreement News Impact on CAAR

Carbon market	-2	-1	0	1	2
California	-0.017	-0.026	-0.032	-0.066	-0.071
	(-1.102)	(-2.099)**	(-3.703)***	(-3.774)***	(-3.661)***
EUA	0.013	-0.138	0.174	-0.059	-0.164
	(0.227)	(-3.060)***	(5.482)***	(-0.934)	(-2.311)**
RGGI	0.141	0.126	0.095	0.111	0.124
	(3.602)***	(3.946)***	(4.194)***	(2.449)**	(2.452)**
Quebec	-0.003	-0.029	-0.033	-0.066	-0.060
	(-0.173)	(-1.853)*	(-2.957)***	(-2.965)***	(-2.437)**
South Korea	0.022	0.060	0.057	0.149	0.148
	(0.610)	(2.089)**	(2.808)***	(3.661)***	(3.241)***
Guangdong	-0.439	0.225	0.062	0.137	0.305
	(-5.552)***	(3.489)***	(1.355)	(1.500)	(2.990)***
Hubei	0.135	0.221	0.147	0.136	0.136
	(1.786)*	(3.590)***	(3.364)***	(1.563)	(-1.490)
Shenzhen	1.162	0.428	0.138	0.319	1.066
	(3.019)***	(1.361)	(0.623)	(0.718)	(2.145)**

The figures represent the CAAR, and the t-statistics are in brackets. The symbols *, ** and *** denote statistical significance at 10% , 5% and 1% levels respectively.

As mentioned in Section 2, the sentiment associated with news is scarcely studied in carbon markets. We aim to contribute to the literature by classifying the types of news using the sentiment score and thereby sorting items into good, bad and neutral news. The difficulty in studying the impact of sentiment on energy commodities lies not only in finding an appropriate proxy for sentiment but also in the lack of theoretical understanding regarding the relationship between sentiment and energy markets (Maslyuk-Escobedo et al., 2017). From the initial investigation of the types of news, all three categories significantly impact abnormal returns. Such effects can cause prices to deviate significantly from their fundamental values. Good news (Table 3.11) has a significant immediate impact for all carbon markets except for Hubei. Good news yielded positive abnormal returns for most carbon markets, except Guangdong, which registers a negative CAAR on the announcement day. However, the returns turn out to be positive post-announcement for Guangdong. Such good news also has an impact over the 5 window days being investigated, which indicates that it is also anticipated by market agents. Existing studies on commodity markets state that returns tend to be more sensitive to downward than to upward sentiment (Allen et al., 2019; Maslyuk-Escobedo et al., 2017) However, bad news (Table 3.12) influences all carbon markets significantly and negatively, which is aligned with the existing literature, as negative sentiment tends to lower prices. A higher impact of such news is observed in the Asian markets, such as South Korea, Guangdong and Shenzhen than in the EU and California. One can again debate the existence of effects and the resilience of carbon markets towards bad news. Previous studies on commodity markets report stronger effects of bad than good news (Dzielinski, 2011; Smales, 2015). However, the findings showcase that bad news are most likely to have an immediate effect rather than a prolonged one. Dzielinski (2011) notes that negative news resolve asymmetric information on average, while positive news does not. Neutral news (Table 3.13) consists of news items that are classified around zero.

Neutral news significantly impacts carbon markets on the announcement date except for Quebec and Shenzhen. The effect is observed in the [-1,+1] window. The magnitude of the impact differs across carbon markets. The EU ETS and California exhibit negative returns.

Table 3.11: Good News Impact on CAAR

Carbon market	-2	-1	0	1	2
California	-0.063	-0.266	0.18	-0.042	-0.118
	(-4.157)***	(20.717)***	(-21.597)***	(-2.801)***	(-6.049)***
EUA	-0.126	-0.256	0.132	0.02	-0.252
	(-2.297)**	(-5.695)***	(4.147)***	(0.37)***	(-3.546)***
RGGI	0.058	-0.035	0.137	0.169	0.019
	(1.493)	(-1.093)	(6.051)***	(4.312)***	(0.378)
Quebec	-0.102	-0.341	0.196	-0.073	-0.186
	(-5.325)***	(-21.806)***	(17.717)***	(-3.809)***	(-7.534)***
South Korea	-0.098	0.13	0.282	0.052	-0.113
	(8.00)***	(4.504)***	(-4.831)***	(1.473)	(-2.49)**
Guangdong	0.155	0.418	-0.435	0.566	0.355
	(-5.501)***	(6.481)***	(3.392)***	(7.159)***	(3.475)***
Hubei	0.148	-0.42	-0.021	-0.382	-0.469
	(1.958)**	(-6.828)***	(-0.489)	(-5.067)***	(-4.814)***
Shenzhen	1.289	-0.134	0.644	0.559	-0.09
	(3.349)***	(-0.428)	(2.899)***	(1.454)	(-0.181)

The figures represent the CAAR, and the t-statistics are in brackets. The symbols *, ** and *** denote statistical significance at 10% , 5% and 1% levels respectively.

These findings indicate that the type of news matters in carbon markets. The degree of impact differs from findings in the literature. While existing studies forecast higher impact from bad news in commodity markets, the converse is true for carbon markets. This might be due to the nature and source of news. Most bad news is related to lobbying and controversies. Based on the results, controversies, uncertainty and lobbying by stakeholders do not significantly

Table 3.12: Bad News Impact on CAAR

Carbon market	-2	-1	0	1	2
California	-0.019	-0.007	-0.051	-0.05	0.041
	(-1.243)	(-0.542)	(-5.877)***	(-3.318)***	(2.093)**
EUA	0.055	0.038	-0.062	-0.083	0.043
	(1.002)	(0.838)	(-1.962)**	(-1.501)	(0.608)
RGGI	0.026	0.104	-0.194	-0.214	-0.135
	(0.669)	(3.26)***	(-8.591)***	(-5.472)***	(-2.674)***
Quebec	-0.045	-0.02	-0.04	-0.047	0.005
	(-2.328)**	(-1.257)	(-3.641)***	(-2.448)**	(0.199)
South Korea	0.179	0.265	-0.215	0.005	0.047
	(5.085)***	(9.214)***	(-10.55)***	(0.148)	(1.023)
Guangdong	-0.1	0.388	-0.511	0.07	0.092
	(-1.266)	(6.017)***	(-11.191)***	(0.884)	(0.905)
Hubei	0.335	0.256	0.075	0.209	-0.029
	(4.444)***	(4.164)***	(1.713)*	(2.770)***	(-0.293)
Shenzhen	-0.028	1.484	-1.094	-0.522	-0.965
	(-0.073)	(4.721)***	(-4.925)***	(-1.357)	(-1.942)*

The figures represent the CAAR, and the t-statistics are in brackets. The symbols *, ** and *** denote statistical significance at 10% , 5% and 1% levels respectively.

impact carbon prices. Thus, this is reflected in the lower impact of negative news.

3.5.1 Cross-Sectional Regression

To identify the potential drivers affecting the cumulative average abnormal returns for the event window, we run a cross-sectional regression of each carbon market's CAAR with a set of explanatory variables:

$$CAR_i(T_1 : T_2) = \alpha + \Sigma_{k=1}^{N} \beta_k X_{ki} + \epsilon_i \tag{3.6}$$

Table 3.13: Neutral News Impact on CAAR

Carbon market	-2	-1	0	1	2
California	0.015	0.009	-0.052	-0.124	-0.143
	(0.965)	(0.708)	(-5.993)***	(-7.153)***	0.011
EUA	-0.052	-0.299	-0.137	-0.534	-0.493
	(-0.945)	(-6.647)***	(-4.318)***	(-8.408)***	(0.051)
RGGI	-0.330	-0.567	0.638	-0.192	-0.125
	(-8.443)***	(-17.737)***	(28.253)***	(-4.248)***	(-0.002)
Quebec	-0.018	0.064	0.034	-0.088	-0.084
	(1.763)*	(4.100)***	(-1.606)	(-3.967)***	(0.023)
South Korea	-0.054	-0.183	-0.184	-0.224	-0.310
	(-1.534)	(-6.355)***	(-9.039)***	(-5.493)***	(0.015)
Guangdong	-0.200	0.154	0.125	0.002	0.617
	(-2.530)**	(2.381)**	(2.748)***	(0.020)	(0.100)
Hubei	-0.324	0.141	-0.307	0.259	0.049
	(-4.300)***	(2.284)**	(-7.041)***	(2.976)***	(-0.003)
Shenzhen	1.240	-0.566	0.224	-1.486	-0.746
	(3.223)***	(-1.802)*	(1.006)	(-3.343)***	(-0.332)

The figures represent the CAAR, and the t-statistics are in brackets. The symbols *, ** and *** denote statistical significance at 10% , 5% and 1% levels respectively.

where: α is the intercept, N is the number of independent variables X_{ik} is the vector of explanatory variables β_k is the coefficient of explanatory variable k, and ϵ_i is the error term

The set of explanatory variables has been drawn from the extant literature as described in Table 3.14. The literature highlights that fluctuations in fossil fuel prices drive consumption and thereby emissions (Wu et al., 2013; Perčić et al., 2020; Zhu et al., 2020b). Natural gas prices seem to be a significant determinant of carbon prices in diverse markets such as the EU and South Korea. Wilson and Staffell (2018) argues that increasing carbon prices creates a fuel switching regime from coal to natural gas. However, a rise in natural gas prices also encourages firms to expand the use of low-cost energy sources such as coal and oil, raising the demand for carbon emissions permits and carbon prices. Chevallier (2011b) and Yu and Mallory (2014) posit that carbon prices are also a function of economic activity. Economic activity responds to exchange rates through international trade. A country with a weaker currency than that of its trading partner experiences higher export demand, which fosters domestic production and ultimately increases carbon credits. Carbon prices can also be influenced by financial markets. Previous studies have gauged this relationship from three main perspectives: general stock indices, energy companies and technology-related companies (Hintermann, 2010; Ji et al., 2019; Zhu et al., 2019b; Yahşi et al., 2019; Paolella and Taschini, 2008; Benz and Trück, 2009). We define the stock indexes used in the present study in Table 3.15.

Table 3.16 presents the results. Overall, the explanatory variables assessed for the given period do not substantially influence the cumulative abnormal returns on carbon prices. However, the CARs of carbon prices are thus impacted by several types of news announcements, e.g., market reforms for the EU ETS and Quebec ETS. The stock index has a significant relationship with carbon prices only in the Quebec ETS. The results are however not striking in terms of economic magnitude. This might be related to the fact that our sample of news items also includes events that can be regarded as less influential by the market.

3.6 Conclusion

Although carbon markets are undoubtedly sensitive to the release of news, this field of research has received little attention from the academic community. Researchers have begun to investigate the impact that the content of news

Table 3.14: Control Variables in the Regression Model

Control Variable	Reference	Source
Fossil Fuel		
Natural Gas	Christiansen et al. (2005); Scholtens and Boersen (2014); Alberola et al. (2008); Hao and Tian (2020)	Refinitiv Global Developed Natural Gas Price Index
Coal Price	Alberola et al. (2007); Scholtens and Boersen (2014); Hao and Tian (2020)	Refinitiv Global Coal Price Index
Oil Price	Koop and Tole (2013); Scholtens and Boersen (2014); Hao and Tian (2020)	Brent Crude Oil Benchmark Index
Economic and Market Variables		
Stock Index	Hintermann (2010); Ji et al. (2019); Zhu et al. (2019a)	Refinitiv
Energy Index	Yahşi et al. (2019)	Refinitiv
Technology Index	Paolella and Taschini (2008); Benz and Trück (2009)	Refinitiv
Exchange Rates	Hao and Tian (2020)	JP Morgan Real Effective rates (CAD, EUR, KRW, RMB, USD)

This table presents the different explanatory variables used in the cross-sectional regressions. The second and third columns show the studies using the variable and the source of the data, respectively.

stories has on carbon markets from a single perspective. In our analysis, we concentrate on seven different categories of news and distinguish among type of news: good, bad and neutral. We additionally contribute by investigating

Table 3.15: Economic and Market Indices

Countries	Broad Stock Index	Energy Index	Technology Index
Canada	Toronto 300	S&P Canadian Energy Sector Index	S&P TSX Canadian Tech Index
China	Shenzhen CSI 300	MSCI International China Energy Index	MSCI International China Technology Index
EU	EURO STOXX Index	EURO STOXX Energy Index	EURO STOXX Tech Index
South Korea	Korea SE Kospi Index	Refinitiv Korea Energy Index	MSCi Korea Tech Index
USA	S&P 500	Refinitiv US Energy Index	Nasdaq 100 Technology Sector

This table presents the different market indexes that are used in the cross-sectional regressions.

eight carbon markets around the world. The findings reveal that carbon prices are less likely to be impacted by negative news that is linked to controversies, uncertainty or lobbying. Good news, however, has a substantial influence on carbon prices.

We also highlight an interesting fact: The effect differs amongst carbon markets. The EU ETS and RGGI, being the largest and oldest ETSs in the world, are significantly impacted by all categories of news compared to other carbon markets, especially Asian markets. The findings on the California and Quebec ETSs are similar. Their existing linkage could have motivated the results. The oldest ETSs are more influenced by announcements than the most recent ETSs. This can also be attributed to the liquidity present in the markets, as less mature markets are also less active. RGGI, EU and California are traded

Table 3.16: Cross-Sectional regression results

	EU	RGGI	California	Quebec	S.Korea	Shenzhen	Hubei	Guangdong
(Intercept)	0.002	−0.000	0.001	0.001	−0.001	0.003	0.002	−0.002
	(0.002)	(0.002)	(0.001)	(0.001)	(0.001)	(0.010)	(0.002)	(0.002)
Natural Gas	0.355^{*}	−0.256	0.032	0.077	-0.324^{**}	−0.260	0.072	−0.284
	(0.204)	(0.158)	(0.072)	(0.075)	(0.146)	(0.973)	(0.229)	(0.237)
Coal	0.069	0.046	−0.011	0.006	−0.035	0.183	0.011	0.068
	(0.077)	(0.059)	(0.027)	(0.028)	(0.055)	(0.367)	(0.086)	(0.089)
Oil	0.010	0.057	0.017	0.011	0.061	0.060	0.104^{*}	−0.032
	(0.053)	(0.040)	(0.018)	(0.020)	(0.038)	(0.255)	(0.060)	(0.062)
Exchange Rate	−0.584	0.071	0.280^{*}	0.186	0.289	0.643	-1.091^{**}	0.218
	(0.417)	(0.314)	(0.143)	(0.153)	(0.297)	(1.992)	(0.469)	(0.486)
Stock Index	0.177	−0.016	−0.013	-0.079^{*}	−0.038	−0.083	−0.027	0.010
	(0.333)	(0.037)	(0.017)	(0.047)	(0.069)	(0.220)	(0.052)	(0.054)
Tech Index	−0.230	−0.144	−0.067	0.051	0.047	−0.349	−0.045	−0.081
	(0.213)	(0.089)	(0.041)	(0.044)	(0.065)	(0.449)	(0.106)	(0.109)
Energy Index	−0.018	−0.008	0.001	0.001	-0.120^{**}	−0.111	−0.011	−0.062
	(0.151)	(0.065)	(0.030)	(0.000)	(0.059)	(0.393)	(0.093)	(0.096)
Lobbying	0.009^{*}	-0.010^{**}	−0.001	0.000	0.001	0.013	-0.016^{***}	0.001
	(0.005)	(0.004)	(0.002)	(0.002)	(0.004)	(0.025)	(0.006)	(0.006)
Linkage	−0.001	0.002	−0.002	−0.003	0.003	−0.016	0.004	−0.006
	(0.006)	(0.004)	(0.002)	(0.002)	(0.004)	(0.027)	(0.006)	(0.007)
New Carbon Market	-0.012^{**}	−0.006	−0.000	−0.000	0.008^{**}	−0.005	−0.009	0.009
	(0.005)	(0.004)	(0.002)	(0.002)	(0.004)	(0.026)	(0.006)	(0.006)
Market Reforms	-0.012^{**}	0.003	-0.003^{*}	-0.006^{***}	−0.004	−0.002	0.000	0.001
	(0.005)	(0.004)	(0.002)	(0.002)	(0.003)	(0.023)	(0.005)	(0.006)
Paris Agreement	0.003	0.007^{*}	−0.002	−0.002	0.004	0.012	−0.001	0.005
	(0.005)	(0.004)	(0.002)	(0.002)	(0.004)	(0.024)	(0.006)	(0.006)
Policy Makers' Ambition	−0.006	0.004	−0.000	−0.001	0.002	−0.039	−0.002	0.012^{*}
	(0.006)	(0.004)	(0.002)	(0.002)	(0.004)	(0.028)	(0.007)	(0.007)
R^2	0.021	0.018	0.009	0.015	0.019	0.003	0.014	0.007
Adj. R^2	0.012	0.008	−0.000	0.005	0.009	−0.006	0.005	−0.003
Num. obs.	1370	1370	1370	1369	1370	1370	1370	1370

The figures represent the coefficient and the standard errors in brackets. The symbols *, ** and *** denote statistical significance at 10% , 5% and 1% levels respectively.

on different contracts, both spot and futures. The Chinese ETS and South Korean ETS have only recently introduced futures contracts. Market participants are more likely to react in highly liquid markets.

In contrast to other energy commodities, the impact of news announcement is not observed in the post-event days. Similarly, it is not anticipated in most carbon markets. Market reforms are the primary category that experiences prolonged effects because such news is foreseen and discussed before being announced.

This paper opens broad and interesting avenues for future research. Each category of news can be investigated over a longer period of time. Carbon markets remain quite young, and more data will be available in the future from the new ETSs. With more refined textual analyses, research can also focus on the in-depth analysis of the news content length and study entire publications, rather than headlines. This would also allow researchers to distinguish between minor and major news announcements. The volatility and volume of returns can also be studied. Relationships between spot and futures markets in all ETSs are also worth investigating. Further, a news index related to the economic and financial news announcements can be constructed to assess their influence on carbon prices. All these avenues need to be addressed in thorough in-depth projects, which are part of our future research agenda.

Chapter 4

Carbon Pricing and Firms

Article title: The Race for Carbon Pricing Amongst Firms

Abstract: Although carbon pricing should have a nontrivial impact on firms' environmental performance, prior studies have paid little attention to the type and number of carbon pricing mechanisms (CPMs) that firms adopt simultaneously. Thus, in this study, we analyse multiple CPMs within a single framework: carbon trading on compliance markets, carbon tax, and internal carbon pricing. Using a sample of 2,303 CPM adopting firms, we capture the relative impact of the presence of single *and* multiple CPMs on firms' environmental performance measured through carbon intensity, energy intensity, and environmental score. The results show that while carbon tax can independently provide significant improvements in environmental performance, carbon trading and internal carbon pricing are ineffective on their own, and can even be detrimental in some cases. There are significant heterogeneities in the effectiveness of CPMs for carbon-intensive sectors versus other sectors and in different regions. Lastly, we provide insights into how environmental innovation and board independence moderate the effect of CPMs on environmental performance.

Keywords: Carbon pricing mechanisms, carbon markets, carbon tax, internal carbon price, environmental performance

JEL: G3, H2, Q5

4.1 Introduction

In an unprecedented era of climate change, carbon pricing has emerged as one of the key instruments to deliver the goals of the Paris Agreement (Tvinnereim and Mehling, 2018; Stiglitz et al., 2017). In 2015, during the Conference of Parties (COP), around 90 countries expressed their intention to introduce carbon pricing as part of their commitments. The number of countries employing a carbon tax and/or a cap-and-trade system has increased in recent years (Metivier et al., 2018). Even prior to COP21, firms sought to transcend environmental expectations through the use of better technological infrastructure in order to curb greenhouse gas (GHG) emissions and budget emission allowances under emission trading systems (Kolk et al., 2008). GHG emission disclosures by firms have been further fuelled in the presence of lobbying and advocacy by non-governmental organisations (Dentoni et al., 2018). Meanwhile, investors and banks have also increasingly become wary of climate risks (Degryse et al., 2023; Ehlers et al., 2022; Bolton and Kacperczyk, 2021), so much so that they sometimes even "pressure the companies in their portfolios to curb emissions" (Azar et al., 2021). Moreover, an increased sensitivity to "climate-risk management" is also driving companies toward internalizing carbon risks (Bolton et al., 2022) to avoid being penalized by capital markets (Matsumura et al., 2014). With these driving forces acting in tandem, climate management practices have increasingly become prominent in the corporate world (Damert and Baumgartner, 2018; Lee, 2012; Hoffman, 2005).

Carbon pricing is amongst the most widely debated climate management practice employed in response to environmental regulations (Zhu et al., 2022; Green, 2021). By setting a price on each ton of emitted carbon dioxide from the business activities, firms bear the additional costs that ultimately reduce their profitability if they are not environmentally conscious. Firms are concerned about carbon pricing regulations negatively impacting their profitability and are thus resorting to reactive or proactive strategies (Fu et al., 2023). Meanwhile, policy makers expect such regulations to stimulate investment in green technology, reduce emissions, and improve environmental performance (Downar et al., 2021). While these effects may occur, the real implications can be more intricate and difficult to capture. Nevertheless, understanding the effectiveness of carbon pricing initiatives is of first-order importance not only for firms and its investors, but also for policy makers.

In this paper, we study the impact of several carbon pricing mechanisms (CPMs) on the firms' environmental performance. Despite the voluminous work on carbon pricing and firm performance, previous studies have always focused on a single pricing mechanism in isolation or have only investigated a macro-level impact (see, for example, Ren et al., 2022; Liu et al., 2017; Martin et al., 2014). There is little work on how one CPM could potentially be more effective than other or whether the deployment of multiple CPMs could potentially accentuate their effectiveness in firms. We fills this gap in the literature by empirically examining the effect of the adoption of multiple CPMs, i.e., carbon markets trading (CM), carbon tax (CT), and internal carbon pricing (ICP), on environmental performance. To be more precise, this paper contributes to literature by addressing the following questions: Do CPMs effectively impact environmental performance? Does the adoption of multiple CPMs amplify this impact? We also run supplementary tests to explore heterogeneities in CPMs effective across industries or regions and to identify potential factors that moderate their effectiveness.

There are several empirical challenges that arise when studying the effect of multiple CPMs' adoption on environmental performance. First, there is no single database that tracks the deployment of different CPMs by firms. Thus, we build a comprehensive database of a wide range of sample firms across the globe between 2012 and 2022, including firms operating under emission trading systems (ETSs) from the EU, California, RGGI, Quebec, and New Zealand. We augment this with the information on firms that are subject to carbon tax policies in 25 countries and firms that have started disclosing internal carbon price over the years. Having an international sample allows us to explore and examine whether there are country- or region-specific heterogeneities in the effectiveness of different CPMs. Second, since our initial analyses are conducted using a database of firms that have adopted at least one CPM over the years, endogeneity concerns arise. For example, there may by significant differences in the CPM adopting and non-adopting firms (or a case of self-selection). We tackle this concern by using propensity score matching (PSM) to examine if there are significant differences in the effectiveness of firms adopting CPMs and those that do not. Third, identifying the relative importance of various CPM adoptions requires that the presence of several CPMs in our sample firms are captured altogether. In other words, studying each CPM adoption separately using a regression framework does not allow for cross-comparison of coefficients of each CPM because systematic differences in samples (or, selection bias) may distort their interpretability. Moreover, alongside the impact of each CPM on environmental performance, the effectiveness of the simultaneous presence of multiple CPMs is also important to identify. We overcome this challenge by coding the simultaneous presence of multiple CPMs in our sample firms over the years and employing a regression framework that can estimate both the relative impact of each CPM on its own and each of their possible combinations.

Using a sample of 2,303 CPM adopting firms, we employ a difference-in-differences approach to compare them to a sample of 1,505 non-CPM adoption firms. In our estimations that control for firm characteristics as well as industry, country, and year heterogeneities, we find that the CPM adopters have better environmental performance than the non-adopters. This result remains robust even when we employ PSM to identify a comparable non-CPM firms for each CPM adopter. However, more importantly, when we delineate each of the CPMs, our results show that carbon tax (CT) is the only CPM that thrives independently in improving environmental performance across all the three environmental proxies. For the other two CPMs, we observe that both CM and ICP are detrimental to carbon intensity and energy intensity. Moreover, while the presence of different combinations of CPMs do not provide any marginal benefits by reducing carbon intensity, the presence of ICP together with either CT or CM can significantly reduce firms' energy intensity. Put differently, in general, CM and ICP need to be paired in order to be effective. The presence of all three types of CPMs together neither impacts carbon intensity or energy intensity in firms. However, it does improve overall environmental performance as proxied by firms' Environmental Score.

Next, we study the differences in how the adoption of CPMs affects carbon-intensive and other sectors differently. We find that CT is the most consistent CPM when it comes to capturing the improvement in environmental performance across all its three proxies. Meanwhile, for non-carbon intensive sectors, when all three CPMs are present in firms together, they appear to be detrimental to environmental performance. The results also generally confirm that CPM is more effective for carbon intensive industries than others. We also examine the regional heterogeneity in the effectiveness of CPMs. Among North American firms, CT reduces carbon emissions by itself and when present along with CM. For the Asian firms, the presence of CM, and more so the presence of CM with ICP, decreases their employed energy intensity, while the presence of CT with ICP has a negative effect on their CO_2 emissions. When all three types of CPMs are present in the firms, they do not have statistically significant impact on environmental performance in any of the regions.

Lastly, we provide some insights into the role of environmental innovation and board independence in making CPMs more effective. The presence of all three types of carbon pricing mechanisms do not reflect on environmental performance unless there is an increase in environmental innovation and board independence.

By aiming is to understand how CPMs impact the firms' environmental performance, our results have important implications for multiple knowledge areas including finance, accounting, environmental economics, and, to some extent, even business ethics. We contribute to these strands of literature in several ways. First, prior studies have shown the impact of carbon emissions and environmental performance on firm valuation (Bolton and Kacperczyk, 2021; Griffin et al., 2017; Oestreich and Tsiakas, 2015; Matsumura et al., 2014), cost of debt (Bolton et al., 2022; Jung et al., 2018), capital structure (Nguyen and Phan, 2020), and dividend policy (Balachandran and Nguyen, 2018). We take a step back and study how different decarbonization initiatives represented by CPMs can affect carbon emissions and environmental performance. Second, and related, a recent strand of literature has examined the effectiveness of CPMs. For instance, Zhu et al. (2022), Liu et al. (2017), and Martin et al. (2014) study the environmental performance of firms when they adopt ICP, CM, and CT, respectively. We contribute to this literature by investigating how these three different CPMs together impact environmental performance. More precisely, by studying three different types of CPMs within a single framework, this paper identifies their individual and combined effects on environmental performance in tandem, given that the firms can adopt these in parallel. This means that we are able to identify those CPMs—individually or in combinations—that are the main drivers of environmental performance. Third, carbon emission regulations and its effectiveness is a widely debated topic among scholars Green (2021); Tvinnereim and Mehling (2018); Bruvoll and Larsen (2004). However, much of the literature has focused largely on the EU (e.g., Dechezleprêtre et al., 2018; Liu et al., 2017; Bel and Joseph, 2015) or China (e.g., Tan and Lin, 2022; Zhang et al., 2021; Shen et al., 2020) with very little evidence exploring global dynamics. We contribute to this literature by studying a large international sample of firms and providing insights on heterogeneities in the effectiveness of different CPMs.

This study also has important policy implications as it provides insights on the optimal number of carbon pricing policies that delivers environmental sustainability. First of all, it helps policy makers to have an overview on the micro level impact of CPMs. It also calls for more guidance and standardization of CPMs globally given the disparities on regional level outcomes.

The rest of the paper is organised as follows. Section 2 outlines the theoretical background by reviewing the relevant literature. Section 3 presents the data and methodology adopted in the study, section 4 analyses the results and discusses the main findings. Lastly, section 5 concludes.

4.2 Literature Review

Carbon pricing is used as a disincentive mechanism to encourage firms to curb their emissions level and stimulate investment and research in low carbon technologies (Andersson, 2019; Best et al., 2020). This section provides an overview on the theoretical motivation for firms adopting carbon pricing mechanisms and elaborates on the relationship between carbon pricing and firms' environmental performance.

4.2.1 Theoretical Underpinning

According to Pinker (2021), environmental problems can be solved, given the right knowledge and proper use of it. Whilst climate risk remains at the centre of attention of international debates, there is a need to investigate the cost related to it (Ehlers et al., 2022; Stroebel and Wurgler, 2021; Jung et al., 2018). This study is grounded on the Porter hypothesis proposed in Porter and Van der Linde (1995) which challenges the conventional view and argues that well-designed regulation can lead to an improvement in environmental quality without any negative effect on economic performance or a ‘win-win’ situation. Thus, positive effects can be seen on both environment and firm performance based on the innovation incentive provided by the regulation (Ambec et al., 2020). In the past decades, the Porter hypothesis has been studied extensively invigorating policy debates, while different versions of the hypothesis have been put forward Zhu et al. (2021). The findings about the impact of environmental regulations on innovation, competitiveness, or firms’ performance remain mixed (Degryse et al., 2023; Guo et al., 2023; Chakraborty and Chatterjee, 2017). Some studies argues that environmental regulation positively influence the productivity levels (see Berman and Bui, 2001; Yang et al., 2012; Hickey et al., 2021 whilst others have found that it results in a decline in productivity (Barbera and McConnell, 1990). When considering these inconsistent findings, it should be remembered that Porter and Van der Linde (1995) emphasize the importance of well-designed regulatory instruments for achieving innovation offsets.

To achieve their imminent emission reduction goals, carbon pricing acts as a means of cost externalization for firms (Bolton et al., 2022; Bose et al., 2021; Nguyen and Phan, 2020). In recent years, some studies related to carbon pricing have explored the Porter’s hypothesis (e.g., Lin and Wesseh Jr, 2020). Essentially, “the mechanism of tradable emission permits as a popular market-oriented regulation system is more promising in efficiently controlling pollution-reduction than traditional command-control instruments” Jin et al. (2022). However, there is also evidence from similar practices in emerging markets showing that these market-oriented systems are not always effective (Tu and Shen, 2015). In this study, we take a global perspective and explore the effectiveness of the adoption of different types of carbon pricing interventions or CPMs.

4.2.2 Carbon Pricing Mechanisms

The cap and trade system employs the total ‘cap’ to attain environmental goals and allows ‘trade’ to achieve the effective scheduling through market regulation. The cap and trade system provides a certain quantity of emissions set by the government, also known as the upper limit. Firms are allowed to trade their allowances in the market but each year must surrender the number of allowances equivalent to their amount of emissions limit. The carbon emissions trading systems (ETS) were introduced after the Kyoto Protocol and is considered as one of the critical drivers for climate ambitions (Ren et al., 2022). The ultimate goal of ETS is to render a minimal cost to achieve the environmental target whilst incentivising decarbonisation and innovation in firms (Wu and Wang, 2022). So far, a number of countries have adopted this mechanism including United States, European Union countries, Japan, Australia, New Zealand, Canada and China (Calel and Dechezleprêtre, 2016). The EU Emission Trading System (EU ETS) is the largest trading system for emissions covering more than 11,000 firms in 30 countries. Following the COVID-19 pandemic, the European Emission Allowances (EUA) price dropped to around €10 and rose back to over €90 in early 2022 (Ohlendorf et al., 2022). Through this system, firms can trade-off their excess emissions with other enterprises that can maintain their emissions below the cap level. Thus, such emission permits have become a valuable resource, which can significantly affect productivity and environmental performance (Du et al., 2013, 2016).

The second type of carbon pricing is more directly applied in the form of carbon taxes, which is a surcharge placed on fuel or energy use. Governments are often in a dilemma to set the appropriate carbon tax legislation to reduce emissions and economic impact. Most governments opt for a progressive carbon taxation which starts with low carbon price and tend to increase over the years until the target is met. The Swedish government adopted a concave carbon tax scheme in 1990, the French government opted for a convex form of carbon tax in 2014, and the Canadian government applied a liner carbon tax scheme in 2018. Scholars have also advocated for carbon tax regulation instead of the cap-and-trade system given that it is an easier regime to implement (Avi-Yonah and Uhlmann, 2009; Inglis and Laffer, 2008). Carbon tax schemes have also been subject to criticisms. Hoel (1996) highlights that carbon intensive tradable sectors should have a lower carbon tax since the tax relocates CO2 emissions to countries with no carbon tax. There is also an ongoing debate about whether the carbon tax should differ across industry sectors given their common or distinctive characteristics (Touboulic et al., 2014).

The third type of CPM is ‘internal carbon pricing’. Internal carbon pricing is voluntarily adopted by companies in two major forms notably *shadow carbon pricing* and *internal carbon tax pricing.* The year 2020 witnessed an exponential growth in net-zero commitments by 1,541 companies from 127 countries and 20% growth in adoption of carbon pricing (World-Bank, 2021). As such internal carbon pricing can play a role by sending a price signal to incentivize low carbon actions and avoid locking in more fossil fuel intensive investments (Popp et al., 2010; Nordhaus, 2014). The surging polutarity of internal carbon pricing can be seen from the fact that largest 500 companies in the world have either already adopted or soon intend to adopt this instrument in the next two years.

From the review presented above, it can deduced that firms can benefit from efficient and effective use of CPM to achieve carbon emission reduction and improve their environmental performance. Despite carbon markets and emission trading systems being known to achieve emission reductions at lower cost when compared to carbon tax (Elkins and Baker, 2001), it is now common to see firms that have multiple carbon pricing policies coexisting with the goal of reducing emissions (Wang et al., 2019b).

4.2.3 Firms' Environmental Performance and Carbon Pricing

The presence of carbon risks and carbon performance have been the centre of attention amongst investors (Griffin et al., 2017; Balachandran and Nguyen, 2018; Azar et al., 2021; Bolton and Kacperczyk, 2021; Kreuzer and Priberny, 2022). Economic theory further emanates that the market failures as a result of climate change need to be addressed using a dedicated policy instrument (Goulder and Parry, 2020). The traditional view is that carbon pricing regulations should increase the cost burden of firms, hence motivating them to transition to lower emissions activities to improve environmental and social welfare (Calvet et al., 2022). However, such view is inconsistent with the classic economic theory that firms are always aiming for cost minimization and such regulations increase their costs (Palmer et al., 1995; Smith and Walsh, 2000; Bolton and Kacperczyk, 2021). As such, carbon pricing policies take various forms as discussed above. There is a wide consensus in the literature that carbon pricing can be a fundamental instrument to combat climate change. Sterner (2007) found that fuel taxes have contributed to emission reductions in Europe and

Japan. Similar results have been reported for carbon taxes in other countries (e.g., Bruvoll and Larsen, 2004). The cap and trade system has also been effective in reducing emissions over the years (Martin et al., 2016). Thus, as with national carbon pricing policies, it is worth investigating whether such effect mirrors at corporate level as well. Internal carbon pricing can also assist in reducing emissions by monetizing it and facilitating internal dialogue on the progress and building awareness Zhu et al. (2022).

The nexus between ETSs and firm performance have been explored in literature through different perspectives: technological innovation (Chen et al., 2021; Rogge et al., 2011), emission reductions (Anderson and Di Maria, 2011; Clò et al., 2017), and financial performance (Costantini and Mazzanti, 2012; Oestreich and Tsiakas, 2015; Downar et al., 2021; Wu and Wang, 2022). Existing studies have found that the EU ETS has only modestly triggered low carbon investment due to the low price for EUA in the early phases (Calel and Dechezleprêtre, 2016). Fullerton and Metcalf (2002) studied the cap and trade system in the presence of a monopoly and the results demonstrate a reduction in welfare gain from environmental restrictions. Zhang et al. (2021) find that ETS could bring the double dividends of green development efficiency and regional carbon equality. Delarue et al. (2008) studied the power sector and confirm emission reductions for firms in the EU. Clò et al. (2017) however found that ETS can have a limited influence on emission reductions due to its allowance losses.

Krass et al. (2013) investigate the impact of carbon tax regulation using a static modelling approach and found that firms react to an increase in taxes and motivate them to transit to low carbon technology. Shen et al. (2021) also stipulate that environmental tax led to increasing investment in green technology and supply chains. Shittu and Baker (2009) study the influence of carbon tax on optimal investment in energy research and development and highlight that the elasticity substitution between fossil and non-fossil energy outputs are positively correlated with investment allocation. Existing studies thus reveal that carbon tax positively impact on low carbon investment and environmental performance. Letmathe and Balakrishnan (2005) review the production mix and quantities under carbon taxes and emission tradings. Li et al. (2017) and Mandell (2008) assess single versus multiple carbon policy in the transport sector and find that extended model with carbon policies is more beneficial for emission reduction. Similarly, Drake et al. (2016) found that firms under cap-and-trade and carbon tax chooses to maximise profit in the second stage of the regulations. Jin et al. (2014) study the impact of carbon policies (both cap-and-trade and carbon tax) on supply chain designs and logistics of a major retailer. Bowen (2011) and Baranzini et al. (2015) found that carbon tax encourages investment in innovative as well as low carbon emitting technologies. However, Faber and Frenken (2009) and Hall and Helmers (2013) are of view that carbon tax can have a negative or insignificant impact on environmental performance due to the 'double externality problem'. The market imperfections impede on the promotion of green activities through carbon pricing. Feichtinger et al. (2022) highlight that carbon tax can lead to a win-win solution of both profits and social welfare through a dynamic differential game.

Another strand of literature is streamed on the performance comparison amongst the carbon pricing. Drake et al. (2016) argue that a firm has greater profit under cap and trade than carbon tax given the price uncertainty and operational flexibility. Drake (2018) also looked into the carbon leakage challenge under carbon tax and found that the regulation still reduce emissions effectively. Chang et al. (2015) looked into three different carbon emission regulations (mandatory carbon emissions, carbon taxes, and cap and trade) and developed two profit maximisation models for manufacturing industry. They found that the carbon tax was more effective than other policies for reducing emissions.

The above papers consider carbon pricing regulations as a mechanism to induce firms to make more informed operational decisions. This paper is aligned with this stream of literature and contributes by paying attention to individual firm's environmental responses to regulations.

4.2.4 Measures of Environmental Performance

Academia and policy makers have paid renewed attention on the measures of environmental performance in the context of carbon pricing. There is an emerging trend of measuring emissions through carbon intensity rather than absolute emissions alone (Matsumura et al., 2014; Pedersen et al., 2021). Firms in major polluting industries are more likely to have different carbon intensities. A study by Fu et al. (2023) shows that emission asymmetries can have a significant role in a firm's decision to improve its environmental performance. Martin et al. (2014) has assessed the impact of carbon tax on the energy intensity and the electricity use by manufacturing firms in UK. Dussaux (2020) evaluated the relationship between carbon tax and environmental performance by adopting the energy use, electricity use, fossil fuel use and CO_2 emissions as proxies. Shen et al. (2020) studies the impact of trading and carbon emissions by Chinese firms using total amount of carbon emissions as a proxy. Other sustainability studies have put forward diverse variables as a proxy for environmental performance. For example, Li and Lu (2016) find that environmental practices such as toxic releases, discharge of polluted water, non compliance with environmental statues, the firm's environmental rating and environmental capital expenditure should be representatives of environmental performance. Zhu et al. (2022) investigating the impact of internal carbon pricing on environmental performance adopted the scope 1 and scope 2 emissions as the firms' total carbon emissions and thus calculated the carbon intensity. Motivated by the empirical review carried out by Dragomir (2018), the latter used metric ton carbon emission per full time equivalent employee (employee intensity) and metric ton carbon emission per revenue (revenue intensity) to avoid problems of firms growing or contracting, which are often accompanied by changes in carbon emissions.

As discussed above, with increasingly strict carbon pricing regulations, it is crucial to study firms' environmental performance under these circumstances. Scholars have been studying in a broad view how carbon policies may affect industry competitiveness when faced with rising costs and foreign imports. The attention has been on the policy and jurisdictions rather than on micro level.

4.3 Research Design

4.3.1 Sample and Data

Carbon pricing has garnered an increasing interest over the past years for the following reasons. Companies need robust policies to survive in a decarbonized economy and thereby use an internal carbon price to mitigate risk. Secondly, investors have growing interest to assess the risk of stranded assets in a pivotal climate policy environment. Thirdly, governments worldwide are imposing a cost on CO2 emissions to mitigate climate change. The latest report by the World Bank states that there are more than 64 CPMs involving ETSs and carbon taxes that are in operation or are soon scheduled for implementation.

Firms trading in Carbon Markets

The existing studies are skewed towards the EU ETS. This study expands to take into account firms operating under diverse ETS such as the RGGI, Cali-

Table 4.1: Positioning of our study in the literature

Authors (year)	Sample	Outcomes	Methodology
Ren et al. (2022)	Panel data from 2006 to 2017 for firms in China	The pilot ETS is related positively to firms' environmental and economic performance and performs better in areas with more stringent emissions caps, and is also positively correlated with firm innovation.	Difference-in-differences
Dussaux (2020)	8,000 french firms in manufacturing sector from 2001-2016	The carbon tax rate reduced manufacturing emissions in 2018 by 5% compared to a no-tax scenario.	Multiple regression
Dechezleprêtre et al. (2018)	Panel data from 2005 to 2012 for firms in the EU ETS	Carbon trading induced emissions reductions in the order of -10% and led to an increase in regulated firms' revenues and fixed assets.	Difference-in-differences
Liu et al. (2017)	Data from the transaction log of EU ETS for the period 2005 to 2012	A comparison of trading performance between the demanders and suppliers was made. For suppliers, the selling requirement positively impacts the average profit, but the impacts become weaker when suppliers have higher selling requirements. For demanders, there was a threshold of a buying requirement. When the buying requirement is higher than the threshold, demanders are inclined to reduce their average cost.	Quantile regression
Zakeri et al. (2015)	Data from a company operating in Australia	Compares the supply chain planning model under carbon taxes and ETS. Carbon trading although imperfect appears to effectively impact on emissions performance and cost.	Green Supply Chain Modelling
Martin et al. (2014)	6,886 manufacturing plants in the UK	Findings show that carbon tax had a strong negative impact on energy intensity and electricity use.	Multiple regression

fornia, Quebec and New Zealand ETS (see Appendix A for details). Unfortunately, the data for the Asian carbon markets namely the Chinese pilot ETS and South Korean market is not available. The list of firms operating under the aforementioned ETS has been retrieved from their respective registry. For the EU ETS, around 6,000 firms have been identified on Refinitiv, 201 for the New Zealand ETS, 434 for Californian ETS, 519 for RGGI and 123 for Quebec ETS. Bearing in mind that most of the firms are private companies in nature, the access to their environmental data is restricted. After retrieving the data, 381 firms trading on compliance carbon markets were included.

Firms subject to Carbon Tax

Carbon tax refers to all taxes for which the rate is explicitly linked to the carbon content of the fuel or where the tax is levied directly on GHG emissions. The term carbon tax is equally used for taxes that apply to GHGs other than CO2 (Dussaux, 2020). The pricing dashboard by the World Bank reports that there are around 27 countries that have adopted carbon tax policies so far (refer to Appendix B for more details). This study considers firms globally that are operating and subject to carbon tax. Firms that are energy intensive and in the manufacturing sector have been included in the sample aligning with existing studies by Dussaux (2020) and Martin et al. (2014). The Refinitiv screener function has been adopted to filter and identify the firms from each country. Around 1505 firms subject to CT have been included in the sample.

Firms adopting Internal Carbon Price

World-Bank (2021) reports that nearly half of the largest 500 companies globally have an internal carbon price or intend to adopt one in the coming two years. The latest Carbon Disclosure Project (CDP) report in 2020 registered a

43% increase in the number of companies adopting internal carbon price within two years. The report also highlights three main motivation for adopting internal carbon price: to drive low-carbon investment, drive energy efficiency, and to change the internal behavior. Refinitiv collects data on the adoption of internal carbon price. We retrieved this data through the Refinitiv screener function and included 628 companies with ICP in the sample.

4.3.2 Variables

Carbon Pricing Mechanism (CPM)

The carbon pricing variables which is categorised into Emission trading system, carbon taxes and internal carbon pricing are adopted as dummy variables which equals to 1 for a firm adopting any one of the CPMs, otherwise 0. Some firms are subject to several pricing mechanisms. Firms can also adopt multiple carbon pricing mechanisms at a time. As shown in Table 4.2, our full sample comprises of a total of 2,303 firms. All the firms in this sample have adopted at least one type of CPM. Pairs of carbon pricing mechanisms (i.e CM∩CT, CM∩ICP, and CT∩ICP) and presence of all types of CPMs together (CM∩CT∩ICP) have also been mapped.

Environmental Performance Variables

Based on the extensive literature review presented in Subsection 4.2.4, the most frequently used environmental performance measures are carbon intensity and energy intensity. Given that this study is looking at firms from more than sixteen countries, there is a lack of data availability to consider other measures of environmental performance. Carbon intensity (CO_2) is defined as the ratio of carbon emissions in thousands of tons over sales. The data has been retrieved

Table 4.2: Adoption of Carbon Pricing Mechanisms

Carbon Pricing Mechanisms=	Only One	Only Two	All Three	Total
CM	274			
CT	1278			
ICP	269			
CM∩CT		149		
CM∩ICP		167		
CT∩ICP		89		
CM∩CT∩ICP			77	
Full CPM Sample				2,303

The table presents the number of firms and their distributions in adoption of carbon pricing mechanisms.CM represents trading on carbon markets, CT for firms subject to carbon tax and ICP for firms adopting internal carbon pricing.

from Refinitiv that reports on the Total CO_2 equivalent emissions to revenues (USD) in million. Energy intensity is often measured by total energy use over output. In firm level studies, expenditure on energy is often used when actual units of energy are not available (Martin et al., 2012). Refinitiv calculates the energy intensity through the total energy use to revenues (USD). Since environmental performance can be driven by several other strategies being implemented within the firm, it is crucial to factor in those elements. Thus, to further obtain a broader perspective of environmental performance beyond carbon emission and energy consumption, the Environmental Score from Refinitiv has also been included.

Control variables

We included all important firm characteristics as control variables. Guo et al. (2019) stipulates that the larger a firm is, the more energy it consumes and therefore its carbon emissions are also relatively high. Firm size (Size) is the natural logarithm of the firm's total assets at the end of the fiscal year. Firm age

(Age) is the number of years since the firm has been founded. Governance factor influencing the corporate decisions such asset liability ratio (leverage) and board members' independence (Board) have also been included (Kim et al., 2020b). Huang et al. (2017) and (Guo et al., 2023) found that technological factors such as Research and Development can have spillover effect on the level of energy consumed and carbon emissions. The Environmental Innovation Score from Refinitiv has been included to proxy for technological factors.

4.3.3 Descriptive Statistics

To ensure data continuity, the longest continuous data of the 2,303 CPM adopting firms spanning 2012 to 2022 has been considered. Table 4.3 presents the descriptive statistics of all the main variables used in this paper. Given the high number of observations of 25,333, the normality of variables become less relevant for such large sample (Wooldridge, 2015).

Table 4.4 provides the correlations between environmental performance and carbon pricing mechanisms. Looking at the independent variables, there is a low correlation present. This table reports the correlation coefficients for the variables. $CO2$ is the log of carbon intensity, $Energy$ is the log of energy intensity and environment is the environment score from ESG grade.

4.3.4 Empirical Methodology

To begin with, we examine the ability of CPMs to improve firms' environmental performance using a difference-in-differences (DiD) approach with a regression that includes industry (Γ_j), country (Λ_k), and year fixed effects (τ_t) to predict the environmental performance. We start with estimations that consider each

Table 4.3: Descriptive Statistics

Variable	Mean	Std Dev	Min	Max
Dependent Variables				
Carbon Intensity	2.408	1.132	1.125	5.632
Energy Intensity	2.702	1.546	1.723	8.195
Environmental Score	3.769	3.570	1.000	12.000
Independent Variables				
CPM	0.604	0.488	0.000	1.000
CM	0.208	0.406	0.000	1.000
CT	0.727	0.445	0.000	1.000
ICP	0.130	0.336	0.000	1.000
CM∩CT	0.026	0.159	0.000	1.000
CM∩ICP	0.036	0.187	0.000	1.000
CT∩ICP	0.034	0.182	0.000	1.000
CM∩CT∩ICP	0.030	0.170	0.000	1.000
Control Variables				
Size	9.281	2.393	0.000	12.573
Growth	9.356	3.322	1.000	11.758
Leverage	0.142	0.157	0.000	2.361
Age	38	34.788	0	190
Innovation	30.64	34.425	0.000	99.89
Board	38.51	33.99	0.000	100.00

Table 4.3 represents the descriptive statistics for the variables used in the main analyses.

of our three CPMs in isolation as follows:

$$EP_{i,t} = \alpha_0 + \beta_0 CPM_{i,t} + X_{i,t} + \Gamma_j + \Lambda_k + \tau_t + \epsilon_{i,t} \tag{4.1}$$

where EP represents the firms' environmental performance measured through carbon intensity (CO_2) energy intensity ($Energy$), and environmental score (Env). The presence of at lease one carbon pricing mechanism for each firm i in year t is represented by CPM either if the firm trades on carbon markets, is subject to carbon tax, or has implemented internal carbon pricing. $X_{i,t}$ is an array of firm-level controls that include size, age, green innovation, and environmental rating. The variable CPM captures both a) the difference between treated (CPM adopters) and control (non-CPM) firms, and b) the difference

Table 4.4: Correlation Matrix

	[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]	[9]	[10]	[11]	[12]	[13]	[14]	[15]
CO2 [1]	1														
Energy [2]	0.012	1													
Env [3]	0.044	0.031	1												
CM [4]	0.019	0.04	0.007	1											
CT [5]	-0.017	-0.014	0.023	0.006	1										
ICP [6]	0.019	0.036	0.025	-0.012	0.001	1									
CM∩CT [7]	0.012	-0.007	-0.004	0.319	0.008	-0.047	1								
CM∩ICP [8]	0.006	0.009	0.015	0.379	0.017	0.013	-0.032	1							
CT∩ICP [9]	0.003	-0.015	-0.003	-0.097	0.007	-0.033	-0.031	-0.037	1						
CM∩CT∩ICP [10]	0.04	0.005	0.018	-0.017	0.018	-0.018	-0.005	0.031	0.013	1					
Age [11]	0.017	0.125	0.039	-0.022	-0.001	-0.003	-0.016	-0.01	0.089	0.03	1				
Size [12]	-0.003	0.254	-0.023	0.016	-0.028	0.006	-0.022	0.021	0.073	0.003	0.199	1			
Lev [13]	0.01	0.288	0.067	0.052	-0.013	0.049	0.024	0.011	-0.018	-0.016	-0.04	0.249	1		
Innov [14]	-0.005	0.136	0.007	0.037	-0.05	-0.005	-0.016	0.041	0.115	0.009	0.224	0.353	0.066	1	
Board [15]	-0.015	0.167	-0.021	0.099	-0.021	0.019	-0.022	0.035	-0.021	-0.042	0.069	0.374	0.18	0.408	1

before and after CPM adoption.

Next, we explore the abilities of each of different CPMs in isolation and in combinations by replicating the empirical model in Equation (4.1). We start with estimations that consider each of our three CPMs in isolation as follows:

$$EP_{i,t} = \alpha_1 + \beta_1 CM_{i,t} + X_{i,t} + \Gamma_j + \Lambda_k + \tau_t + \epsilon_{i,t} \tag{4.2a}$$

$$EP_{i,t} = \alpha_2 + \beta_2 CT_{i,t} + X_{i,t} + \Gamma_j + \Lambda_k + \tau_t + \epsilon_{i,t} \tag{4.2b}$$

$$EP_{i,t} = \alpha_3 + \beta_3 ICP_{i,t} + X_{i,t} + \Gamma_j + \Lambda_k + \tau_t + \epsilon_{i,t} \tag{4.2c}$$

where environmental performance ($EP_{i,t}$), firm-specific controls ($X_{i,t}$) are same as defined in Equation (4.1), but the three different CPMs within each firm i in year t are represented by CM for firms trading on carbon markets, CT for firms subject to carbon tax, and ICP for firms that have implemented internal carbon pricing.

We further examine what impact the presence of more than one carbon pricing mechanisms have on environmental performance. The following models are used to understand the joint effects when various possible combinations of carbon pricing mechanisms co-exist within a firm:

$$EP_{i,t} = \alpha_4 + \beta_4 (CM \cap CT)_{i,t} + X_{i,t} + \Gamma_j + \Lambda_k + \tau_t + \epsilon_{i,t} \tag{4.3a}$$

$$EP_{i,t} = \alpha_5 + \beta_5 (CM \cap ICP)_{i,t} + X_{i,t} + \Gamma_j + \Lambda_k + \tau_t + \epsilon_{i,t} \tag{4.3b}$$

$$EP_{i,t} = \alpha_6 + \beta_6 (CT \cap ICP)_{i,t} + X_{i,t} + \Gamma_j + \Lambda_k + \tau_t + \epsilon_{i,t} \tag{4.3c}$$

$$EP_{i,t} = \alpha_7 + \beta_7 (CM \cap CT \cap ICP)_{i,t} + X_{i,t} + \Gamma_j + \Lambda_k + \tau_t + \epsilon_{i,t} \tag{4.3d}$$

where $CM \cap CT$, $CM \cap ICP$, and $CT \cap ICP$ represent the firms' that have any of the two carbon pricing mechanisms co-existing, while the term $CM \cap CT \cap ICP$ captures the instances when all the three mechanisms exist in unison. The other aspects of this empirical specification are similar to those in Equations (4.1) and include firm controls $X_{i,t}$, industry fixed effects (Γ_j) and year fixed effects (τ_t).

Lastly, we run a horse race regression to determine within a single framework whether the benefits of the existence of one or multiple carbon pricing mechanisms outweigh the others. This is done using the following empirical specification:

$$\begin{aligned} EP_{i,t} = & \alpha + \beta_1 CM_{i,t} + \beta_2 CT_{i,t} + \beta_3 ICP_{i,t} \\ & + \beta_4 (CM \cap CT)_{i,t} + \beta_5 (CM \cap ICP)_{i,t} + \beta_6 (CT \cap ICP)_{i,t} \\ & + \beta_7 (CM \cap CT \cap ICP)_{i,t} + X_{i,t} + \Gamma_j + \Lambda_k + \tau_t + \epsilon_{i,t} \end{aligned} \tag{4.4}$$

4.4 Empirical Findings and Discussions

4.4.1 Carbon Pricing Mechanisms and Environmental Performance

Environmental performance is subject to diverse strategies and hence, it is important to test whether the presence of carbon pricing mechanisms matter. The data used above comprised of firms adopting at least one carbon pricing mechanisms. A control group has been added with firms that do not adopt any carbon pricing mechanism. The control group has been constructed by extracting data of firms in countries whereby there is no carbon regulations (cap and trade and carbon tax) and nor have they implemented an internal carbon price. Table 4.5 confirms the first hypothesis that carbon pricing does have an impact on environmental performance. The presence of atleast one carbon

	Model 1	Model 2	Model 3
Carbon Pricing Mechanism	-0.256^{***}	-0.315	2.460^{***}
	(0.217)	(0.232)	(0.499)
Age	0.001^{***}	0.001^{***}	0.001^{**}
	(0.000)	(0.000)	(0.000)
Leverage	0.253^{***}	1.044^{***}	-0.149^{*}
	(0.034)	(0.037)	(0.079)
Innovation	0.003^{***}	0.006^{***}	-0.008^{***}
	(0.000)	(0.000)	(0.000)
Size	-0.001	0.028^{***}	0.026^{***}
	(0.003)	(0.003)	(0.006)
Board	0.004^{***}	0.010^{***}	0.017^{***}
	(0.000)	(0.000)	(0.000)
Year fixed effect	Yes	Yes	Yes
Industry fixed effect	Yes	Yes	Yes
Country fixed effect	Yes	Yes	Yes
R^2	0.218	0.440	0.088
Adj. R^2	0.214	0.438	0.084
Num. obs.	41888	41888	41888

$^{***}p < 0.01$; $^{**}p < 0.05$; $^{*}p < 0.1$

Table 4.5: Impact of Carbon Pricing Mechanism on Environmental Performance

pricing mechanism in a firm improves the carbon intensity and environmental score. However, insignificant results has been deduced for energy intensity.

Propensity Score Matching (PSM)

The propensity score matching (PSM) method is employed to further address the endogeneity concern regarding the relationship between carbon pricing mechanisms and environmental performance. The PSM is used to emulate the balance between the treatment (firms adopting carbon pricing) and control group (firms that do not adopt carbon pricing) based on their propensity score. The matching has been carried out based on the size and leverage of the firms. The matching algorithm has come up with 1,505 pairs in the treatment and control groups, which are found to be similar on all important firm characteristics (see Table 4.6).

Table 4.6: Differences in firm characteristics after PSM

Variables	Treatment $(N = 1505)$	Control $(N = 1505)$	Difference	t-statistics
Carbon Intensity	1.304	0.975	0.329	(-0.724)
Energy Intensity	1.699	1.827	0.128	(1.575)
Env Score	3.539	4.289	0.750	(1.070)
Size	9.338	9.487	0.149	(-1.620)
Age	35.789	39.682	3.893	(-1.110)
Leverage	0.230	0.160	0.07	(-0.760)
Innovation	33.062	29.218	3.844	(1.050)
Board Independence	37.14	38.16	1.02	(0.280)

***, **, and * denote the significance at the 0.01, 0.05, and 0.10 levels respectively.

Table 4.7 reports the regression results based on the propensity matching estimates which confirm that firms with at least one carbon pricing mechanisms is likely to experience an improvement in environmental performance through carbon intensity and environmental score.

Table 4.7: Regression results on PSM sample

	Model 1	Model 2	Model 3
Carbon Pricing Mechanism	-0.032^{***}	0.003	0.153^{***}
	(0.009)	(0.013)	(0.024)
Age	0.002^{***}	0.003^{***}	-0.002^{***}
	(0.000)	(0.000)	(0.000)
Leverage	0.388^{***}	0.438^{***}	0.105
	(0.032)	(0.047)	(0.084)
Innovation	0.008^{***}	0.013^{***}	-0.026^{***}
	(0.000)	(0.000)	(0.000)
Size	0.022^{***}	0.037^{***}	0.101^{***}
	(0.003)	(0.004)	(0.007)
Board	0.012^{***}	0.021^{***}	0.047^{***}
	(0.000)	(0.000)	(0.000)
Year fixed effect	Yes	Yes	Yes
Industry fixed effect	Yes	Yes	Yes
Country fixed effect	Yes	Yes	Yes
R^2	0.585	0.536	0.392
Adj. R^2	0.582	0.534	0.389
Num. obs.	33110	33110	33110

$^{***}p < 0.01$; $^{**}p < 0.05$; $^{*}p < 0.1$

Disentangling the Importance of Different CPMs

Tables 4.8, 4.9 and 4.10 present the results from the cross-sectional regressions using three different measures of environmental performance. The first three Models (1-3) show the regression from the adoption of a single CPM: model (1) represents firms trading on compliance carbon markets, model (2) for firms subject to carbon tax, and model (3) for firms adopting internal carbon pricing only. The second set of three models (4-6) presents the results when the firms have adopted two carbon pricing mechanisms: model (4) for trading on compliance carbon market and carbon tax, model (5) for trading on compliance carbon market and internal carbon price, and model(6) for carbon tax and internal carbon price. Model (7) assesses the set of firms that adopt all three types of CPMs together. Finally, model (8) runs the horse race regression of all possible combinations of CPM adoptions.

The empirical results shed light on the adoption of carbon pricing mechanisms. Pedersen et al. (2021) report that companies facing rising carbon prices, should ideally increase production quantity whilst decreasing the volume of emissions simultaneously, thus a negative relationship is expected to generate between carbon pricing and carbon emissions. In case of sole carbon pricing, carbon trading and internal carbon pricing have significant but positive relationship on carbon intensity whilst firms subject to carbon tax have significant and negative impact impact on carbon intensity. Firms that adopt pairs of carbon pricing mechanisms from models (4) and (6) only witnessed significant impact through carbon trading and internal carbon pricing. Finally, firms subject to all three types of carbon pricing mechanisms do not experience significant impact on the carbon intensity.

The horse race regressions on energy intensity (Table 4.9) similar results as the carbon intensity. Models (1)- (3) from a single carbon pricing mechanisms

Table 4.8: Horse race regressions on Carbon Intensity

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
CM	0.076***							0.072***
	(0.017)							(0.019)
CT		-0.041^{***}						-0.044^{***}
		(0.015)						(0.015)
ICP			0.042**					0.045**
			(0.019)					(0.019)
CM∩CT				0.067				0.016
				(0.041)				(0.044)
CM∩ICP					0.079**			0.015
					(0.036)			(0.039)
CT∩ICP						-0.021		-0.006
						(0.037)		(0.037)
CM∩CT∩ICP							0.005	0.005
							(0.030)	(0.030)
Age	0.001***	0.001***	0.001***	0.001***	0.001***	0.001***	0.001***	0.001***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Board Independence	0.004***	0.004***	0.004***	0.004***	0.004	0.004***	0.004***	0.004***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Size	0.027***	0.027***	0.027***	0.027***	0.027***	0.027***	0.027***	0.027***
	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)
Env Innovation	0.001***	0.001***	0.001***	0.001***	0.001***	0.001***	0.001***	0.001***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Leverage	0.099**	0.102**	0.098**	0.100**	0.104**	0.103**	0.104**	0.094**
	(0.046)	(0.046)	(0.046)	(0.046)	(0.046)	(0.046)	(0.046)	(0.046)
Year fixed effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Industry fixed effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Country fixed effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
R^2	0.403	0.403	0.403	0.403	0.403	0.403	0.403	0.403
Adj. R^2	0.401	0.401	0.401	0.401	0.401	0.401	0.401	0.401
Num. obs.	25333	25333	25333	25333	25333	25333	25333	25333

$^{***}p < 0.01$; $^{**}p < 0.05$; $^{*}p < 0.1$. The table reports the coefficient estimates and the standard errors in bracket.

witness positive significant relationship from carbon trading and internal carbon pricing whilst carbon tax seems to induce emissions reduction. The pairwise carbon pricing mechanisms from models (4)-(6) shows carbon trading coupled with carbon tax instead increases emissions whilst carbon tax coupled with internal carbon pricing results as reduction of emissions. Finally, firms adopting all three carbon pricing mechanisms do not witness any significant impact on energy intensity.

From Table 4.10, the baseline regression results show that only carbon tax mechanism have a positive and significant impact on environmental score. From the horse race results, carbon trading and internal carbon pricing influence the score. Carbon trading and internal carbon pricing have to be paired so that

Table 4.9: Horse race regressions on Energy Intensity

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
CM	0.071^{***}							0.085^{***}
	(0.014)							(0.017)
CT		-0.036^{***}						-0.036^{***}
		(0.013)						(0.013)
ICP			0.044^{***}					0.045^{***}
			(0.017)					(0.017)
CM∩CT				0.076^{**}				0.003
				(0.036)				(0.038)
CM∩ICP					-0.042			-0.112^{***}
					(0.031)			(0.034)
CT∩ICP						-0.164^{***}		-0.150^{***}
						(0.032)		(0.032)
CM∩CT∩ICP							0.022	0.031
							(0.034)	(0.034)
Age	0.002^{***}	0.002^{***}	0.002^{***}	0.002^{***}	0.002^{***}	0.002^{***}	0.002^{***}	0.002^{***}
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Board Independence	0.004^{***}	0.004^{***}	0.004^{***}	0.004^{***}	0.004^{***}	0.004^{***}	0.004^{***}	0.004^{***}
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Size	0.049^{***}	0.049^{***}	0.049^{***}	0.049^{***}	0.049^{***}	0.049^{***}	0.049^{***}	0.049^{***}
	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)
Env Innovation	0.001^{***}	0.001^{***}	0.001^{***}	0.001^{***}	0.001^{***}	0.001^{***}	0.001^{***}	0.001^{***}
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Leverage	1.266^{***}	1.269^{***}	1.264^{***}	1.266^{***}	1.269^{***}	1.271^{***}	1.269^{***}	1.259^{***}
	(0.040)	(0.040)	(0.040)	(0.040)	(0.040)	(0.040)	(0.040)	(0.040)
Year fixed effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Industry fixed effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Country fixed effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
R^2	0.359	0.358	0.358	0.358	0.358	0.359	0.358	0.360
Adj. R^2	0.357	0.356	0.356	0.356	0.356	0.357	0.356	0.358
Num. obs.	25333	25333	25333	25333	25333	25333	25333	25333

$^{***}p < 0.01$; $^{**}p < 0.05$; $^{*}p < 0.1$. The table reports the coefficient estimates and the standard errors in bracket.

they can influence the score. Unlike the impact on carbon and energy intensity, the adoption of the three types of carbon pricing mechanisms improves the environmental score. The environmental score is composed of three pillars; emissions, resource use and innovation. The carbon and energy intensity fall under the emission and resource pillar. The presence of all types of carbon pricing mechanism might be able to foster innovation and influence the other environmental strategies thus resulting in a better score.

Energy-Intensive versus Other Industries

Carbon pricing mechanisms are popular amongst energy intensive industries such that it can directly directly affect energy price and the cost of energy use,

Table 4.10: Horse race regressions on Environmental Score

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
CM	0.004							0.007
	(0.005)							(0.040)
CT		0.103***						0.100***
		(0.031)						(0.031)
ICP			0.024					0.024
			(0.036)					(0.036)
CM∩CT				−0.037				−0.028
				(0.086)				(0.092)
CM∩ICP					0.124*			0.099
					(0.075)			(0.081)
CT∩ICP						−0.038		−0.030
						(0.076)		(0.077)
CM∩CT∩ICP							0.180**	0.176**
							(0.081)	(0.081)
Age	0.002***	0.002***	0.002***	0.002***	0.002***	0.002***	0.002***	0.002***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Board Independence	0.019**	0.019**	0.019**	0.019**	0.019**	0.019**	0.019**	0.019**
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Size	0.086***	0.086***	0.086***	0.086***	0.086***	0.086***	0.086***	0.086***
	(0.007)	(0.007)	(0.007)	(0.007)	(0.007)	(0.007)	(0.007)	(0.007)
Env Innovation	0.000	0.001**	0.001*	0.001*	0.001*	0.001*	0.001*	0.001**
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Leverage	0.003	0.003	0.003	0.004	0.005	0.003	0.004	0.004
	(0.096)	(0.096)	(0.096)	(0.096)	(0.096)	(0.096)	(0.096)	(0.096)
Year fixed effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Industry fixed effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Country fixed effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
R^2	0.245	0.245	0.245	0.245	0.245	0.245	0.245	0.245
Adj. R^2	0.243	0.243	0.243	0.243	0.243	0.243	0.243	0.243
Num. obs.	25333	25333	25333	25333	25333	25333	25333	25333

$^{***}p < 0.01$; $^{**}p < 0.05$; $^{*}p < 0.1$. The table reports the coefficient estimates and the standard errors in bracket.

which leads to increase in the total cost of these industries. To further assess the role of carbon pricing mechanisms, a sample of high carbon intensive industries has been examined as per Table 4.11. The sample has been derived through The Climate Watch data [1] by World Resources Institute flags Energy, Transport, Agriculture, Forestry and Other Land Use (AFOLU) and the Manufacturing as the carbon intensive sectors. A first generic analysis shows that the presence of carbon pricing mechanisms in carbon intensive industries is significantly impacting on environmental performance compared to the rest of the sectors. However, it can be seen that implementation of carbon tax mechanism can accelerate the reduction in energy use and ultimately carbon emissions

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[1] https://ourworldindata.org/emissions-by-sector

Table 4.11: Carbon Intensive Industries vs The rest

	Carbon-Intensive Sectors			Other Sectors		
	Model 1	Model 2	Model 3	Model 1	Model 2	Model 3
CM	0.103^{***}	0.116^{***}	0.040	−0.001	0.003	−0.073
	(0.020)	(0.022)	(0.044)	(0.021)	(0.024)	(0.059)
CT	-0.086^{***}	-0.053^{***}	0.127^{***}	0.003	−0.015	0.068
	(0.016)	(0.018)	(0.034)	(0.016)	(0.018)	(0.044)
ICP	−0.023	−0.029	−0.031	0.099^{***}	0.146^{***}	0.090
	(0.022)	(0.024)	(0.047)	(0.020)	(0.023)	(0.057)
CM∩CT	0.149^{***}	−0.014	−0.119	0.239^{***}	0.105^{**}	−0.147
	(0.050)	(0.056)	(0.108)	(0.044)	(0.050)	(0.124)
CM∩ICP	0.024	-0.175^{***}	0.221^{***}	-0.162^{***}	−0.025	0.136
	(0.039)	(0.043)	(0.084)	(0.047)	(0.053)	(0.132)
CT∩ICP	−0.057	−0.027	-0.272^{***}	-0.184^{***}	-0.318^{***}	-1.237^{***}
	(0.040)	(0.044)	(0.086)	(0.039)	(0.044)	(0.108)
CM∩CT∩ICP	−0.015	0.006	−0.065	0.086^{**}	0.097^{**}	-0.492^{***}
	(0.043)	(0.047)	(0.092)	(0.040)	(0.045)	(0.111)
Year fixed effect	Yes	Yes	Yes	Yes	Yes	Yes
Country fixed effect	Yes	Yes	Yes	Yes	Yes	Yes
R^2	0.262	0.242	0.220	0.296	0.344	0.307
Adj. R^2	0.259	0.238	0.216	0.291	0.340	0.303
Num. obs.	15059	15059	15059	10274	10274	10274

$^{***}p < 0.01$; $^{**}p < 0.05$; $^{*}p < 0.1$

Columns denoted with (1), (2) and (3) have been regressed against carbon intensity, energy intensity and environmental score for High Carbon Intensive industries respectively.Columns denoted with (4), (5) and (6) have been regressed against carbon intensity, energy intensity and environmental score for the rest of the industries respectively

whilst simultaneously improving the environmental performance. The results are similar to Fu et al. (2023) who found that the introduction of carbon tax is more likely to benefit carbon inefficient firm.

Carbon trading and internal carbon pricing should be paired in order to induce a reduction in energy intensity. The presence of three type of carbon pricing mechanisms does not influence any environmental performance measures amongst carbon intensive industries. It is noteworthy to analyse how the non carbon intensive industries react to carbon pricing mechanisms. Internal carbon pricing mechanism is dominating amongst the other sectors. This might be related to the fact that carbon intensive industries are most likely to be under the coverage of emission trading systems and subject to carbon tax. Whilst the other sectors left out resort to the adoption of internal carbon pricing which is voluntary in nature. However, internal carbon pricing does not seem to be improving the environmental performance. It only manifests when paired with

Table 4.12: Carbon Pricing Mechanisms at Regional Level

	European Union (EU)			Asia			North America		
	Model 1	Model 2	Model 3	Model 1	Model 2	Model 3	Model 1	Model 2	Model 3
CM	−0.019	−0.046	0.135	−0.062	−0.076*	0.137	−0.008	0.047	0.200
	(0.026)	(0.037)	(0.090)	(0.039)	(0.041)	(0.134)	(0.047)	(0.069)	(0.168)
CT	0.025	0.098***	−0.042	−0.029	−0.025	0.284**	−0.278***	−0.020	0.023
	(0.020)	(0.029)	(0.069)	(0.022)	(0.026)	(0.061)	(0.030)	(0.059)	(0.144)
ICP	0.068**	0.050	0.364***	−0.018	0.041	−0.021	0.039	0.094	0.262
	(0.027)	(0.038)	(0.091)	(0.029)	(0.033)	(0.079)	(0.038)	(0.080)	(0.194)
CM∩CT	−0.016	0.071	−0.177	−0.040	−0.045	−0.289	−0.310*	−0.354	0.341
	(0.055)	(0.077)	(0.187)	(0.093)	(0.094)	(0.320)	(0.175)	(0.245)	(0.617)
CM∩ICP	−0.051	0.104	−0.088	0.098	−0.527***	0.040	−0.054	−0.526*	−1.001
	(0.051)	(0.072)	(0.174)	(0.074)	(0.085)	(0.202)	(0.215)	(0.317)	(0.763)
CT∩ICP	−0.089	−0.280***	−0.059	−0.108**	−0.049	−0.271	−0.092	0.034	−0.271
	(0.061)	(0.052)	(0.167)	(0.038)	(0.043)	(0.220)	(0.175)	(0.257)	(0.620)
CM∩CT∩ICP	0.027	−0.142	0.280	−0.028	0.048	−0.173	0.031	0.010	−0.057
	(0.052)	(0.073)	(0.178)	(0.069)	(0.097)	(0.237)	(0.289)	(0.196)	(0.470)
Year fixed effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Industry fixed effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Country fixed effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
R^2	0.218	0.162	0.202	0.209	0.147	0.062	0.257	0.170	0.093
Adj. R^2	0.216	0.160	0.199	0.206	0.142	0.057	0.252	0.164	0.086
Num. obs.	13013	13013	13013	6248	6248	6248	2761	2761	2761

$^{***}p < 0.01$; $^{**}p < 0.05$; $^{*}p < 0.1$

Columns denoted with (1), (2) and (3) have been regressed against carbon intensity, energy intensity and environmental score respectively

carbon tax. Trinks et al. (2022) found that naturally, the internal carbon price might also reflect different capital asset characteristics, such as investment horizon, which are primarily sector-related which reduces uncertainty and allowing it to have more impact.

Heterogeneities at Regional Levels

This study further investigates the adoption of carbon pricing mechanisms at regional level. Three regions that have adopted carbon trading systems and carbon taxes have been included in the sub samples; Europe, Asia and North America. Whilst carbon market did not have an impact on environmental performance on its own, it can be seen that in Asia, its presence is significant. The impact of carbon tax as an independent carbon pricing mechanism is felt on different environmental performances across the regions. In EU, it has a positive and significant impact on energy intensity, in Asia it helps to improve the environmental score and in North America, it reduces the carbon intensity. Internal carbon pricing has significant impact only in Europe. It seems that the adoption of ICP does not motivate firms to reduce their carbon intensity in EU whilst it does help to improve their environmental score overall. The preference and impact of adopting pairs of carbon pricing mechanisms differs as well. In Europe, the adoption of carbon tax coupled with internal carbon pricing is leading to reduction in energy intensity. Asian firm are likely to experience reduction in carbon and energy intensity through the pairs of carbon trading plus internal carbon pricing and carbon tax and internal carbon pricing respectively. North American firms shall benefit through carbon trading and internal carbon pricing. The adoption of the three types of carbon pricing mechanisms simultaneously do not lead to improved environmental performance even on regional level.

4.4.2 The Roles of Environmental Innovation and Board Independence

Environmental Innovation as moderating factor

Firms engage in carbon pricing mechanism to comply with government regulations, reduce costs or meet stakeholder expectations. Environmental innovation is deemed to improve the environmental aspects and efficiency of the firms through cost saving or by generating new income (Wedari et al., 2023). The presence of environmental innovation may influence the adoption of carbon pricing mechanisms and eventually the environmental performance. Existing studies have portrayed environmental innovation from three angles. First, firms interact with external stakeholders who provide resources which are ultimately invested in innovation (Crilly et al., 2012). Secondly, through shared values brought by carbon pricing mechanisms, a positive organisation atmosphere is created which enhances the firms' ability to innovate Thus, the latter has been tested as a moderating factor in the model (Tachizawa and Wong, 2015). Thirdly, carbon pricing induces customers' loyalty which encourages them to innovate (Kim, 2017). The interaction term between carbon pricing mechanisms and environmental innovation is introduced in the model.

The coefficient for the interaction term between carbon pricing mechanism(s) and environmental innovation is significant only for $Carbon\ Tax$ x $Innovation$ for carbon intensity, ICP x $Innovation$ for environmental score, $CM \cap ICP$ x $Innovation$ for carbon intensity and energy intensity, $CT \cap ICP$ x $Innovation$ for energy intensity and $CM \cap CT \cap ICP$ x $Innovation$ for carbon intensity. It implies that the improved environmental performance caused by the carbon pricing mechanisms differ across firms with different environmental innovation commitments.

Board Independence as moderating factor

Liao et al. (2015) argue that a firm's climate strategy often involve large investments with complex consequences that may affect stakeholder groups in distinct ways- for example some stakeholders may focus on financial returns whereas others are concerned with the environmental impact, so a board's environmental decision may represent the compromise of conflicting demands. Therefore, a board must be sufficiently independent to address issues raised by various stakeholders. Appointment of independent directors, who are less aligned with management and are more likely to be inclined to encourage firms to adopt carbon pricing mechanism demanded by stakeholders, is an effective monitoring mechanism that restricts the opportunistic behaviours of top executives assumed by agency theory (Hillman and Dalziel, 2003). Thus, an interaction term comprising of carbon pricing mechanisms and board independence has been introduced in the model. The results show that the coefficient of interaction between $CarbonPricingMechanisms$ x $Board\ Independence$ is significant for CT x $Board\ Independence$ for carbon intensity and environmental score, ICP x $Board\ Independence$ for energy intensity and environmental score, $CM \cap CT$ x $Board\ Independence$ for carbon and energy intensity, $CT \cap ICP$ x $Board\ Independence$ for energy intensity and environmental score and $CM \cap CT \cap ICP$ x $Board\ Independence$ for environmental score.

Drawing upon the results, the adoption of $CM \cap CT \cap ICP$ had previously generated insignificant findings and it did not influence the environmental performance. However, when the interaction with innovation and board independence has been tested, the latter generated significant results. Implementing three types of carbon pricing mechanisms would necessitate further improvements in innovation and board independence such that their benefits could transcend to improving the environmental performance. It can be argued that the adoption of multiple carbon pricing mechanisms at a time also means that more resources need to be mobilised and invested, there is more pressure to reduce emissions from diverse stakeholders. If firms are unable to efficiently unlock the resources, innovation and have the support of the board, carbon pricing mechanisms are thus not effective as an environmental measure.

4.4.3 Discussions

This study assesses the adoption of multiple types of CPMs and their influence on environmental performance measured through carbon intensity, energy intensity, and environmental score. The first discussion that stems from the adoption of carbon pricing mechanisms is that carbon tax has much more influence that carbon trading or internal carbon pricing. It can be deduced that carbon tax had more significant impact on inducing reduction on emissions and energy consumption. Unlike under cap and trade, where firms have allocated emission allowances for free, under a carbon tax, firms need to compensate for their emissions which affects their profitability and motivates them to decarbonise (Fu et al., 2023). Further, carbon taxes provide more certainty over carbon trading. Future abatement costs are however uncertain (for example, due to uncertainty over fuel prices and the availability and costs of clean technologies) and governments cannot choose certainty over both prices and emissions. Under carbon taxation, governments can provide certainty over future emissions prices by specifying the future trajectory of tax rates. Parry et al. (2022) highlight that such uncertainty on price associated with carbon trading can deter the adoption of clean energy and technology and ultimately not inducing improvement in environmental performance.

Carbon trading ignores small scale emitters in sectors covered by the ETS but their share of emissions can also be modest. Carbon trading suffers from drawbacks in countries with limited institutional capacity or with concentrated trading due to limited number of firms. Internal carbon pricing significantly influence carbon intensity and energy intensiy. However, it does not lead to an overall environmental performance. The CDP reports that the disclosed level of internal carbon price exceeds the ’external’ carbon prices under carbon pricing systems and legislations suggesting that the latter might reflect more concern over future carbon legislation. However, the presence of internal carbon price is substantially divergent across firms which can imply uncertainty over the setting the price.

The study puts forward the adoption of multiple carbon pricing mechanisms amongst firm. Whilst carbon trading and internal carbon pricing on their own could not improve environmental performance, it can be noted that when they are paired, more significant results are obtained. Trinks et al. (2022) argues that the use of internal carbon price is driven by external carbon constraints and by the firms’ exposure to formal carbon pricing. The presence of societal risk and stringent climate policies through ETS can provide predictable pathways to help firms mitigate their misalignment of their investments using the internal carbon price. The implementation of both carbon taxes and ETSs are common in some countries. Taxes have been applied to the same emissions sources as ETSs to establish a more robust price signal. However, throughout this study, bilateral adoption of carbon pricing mechanisms of tax and trading do not effectively impact on firms.

A small sample of firms had adopted all the types of carbon pricing mechanisms i.e $CM \cap CT \cap ICP$. The results are not in favour of the robust presence of carbon pricing mechanisms and are insignificant. Further analysis show that the potential of multiple carbon pricing mechanisms can be unlocked through environmental innovation and board independence. Firms under this sample are subject to increasing costs and pressure from diverse stakeholders.

4.4.4 Policy Implications

Realizing deep decarbonization at the pace necessary to mitigate the worst impacts of climate change has emerged as a pressing challenge for policymakers. Carbon pricing has been crowned as an effective decarbonisation policy as it helps in making low and zero carbon energy more competitive compared to high carbon alternatives. This study brings insight to policymakers on the effectiveness of carbon pricing mechanisms on micro level.

Economics are overwhelmingly supporting the implementation of the effective carbon price to be able to encourage decarbonisation. However, the long focus has been on a metric called the social cost of carbon (an estimate of the marginal damages of an additional ton of CO_2 emissions). Kaufman et al. (2020) reports on the governing uncertainty for using social cost of carbon metric. International climate change negotiations are rapidly shifting to net-zero emissions targets and this has to reflect in the carbon price calculation by policy makers and firms. Right now, there are no international standards that businesses should meet when setting up their internal price on carbon and this inappropriate rate being adopted might not be significant to induce emission reductions.

Models that simulate economic and energy systems are built using historical data on production, consumption and market dynamics, which may be a reasonable assumption in the near term. Focusing on the near term means that CO2 price estimates should not be unduly influenced by assumptions about the highly uncertain long-term evolution of technologies and behaviour. On the carbon trading front, the price volatility can be controlled through mechanisms such as price floors, banking/borrowing provisions and by having a transparent future emissions cap.

Nations such as Finland, Norway, Sweden and Denmark are the frontrunners in launching carbon regulations in early 1990s. The time horizon should be based on a steady state of spatial interactions in tax policies over time. In some scenarios, firms might need more time to adjust their strategies in response to a policy shock on national or international level.

4.5 Conclusion

With growing emphasis on adoption of carbon pricing mechanisms worldwide, there is a growing demand for research on the adoption of CPMs and whether the latter is able to induce emission reductions and improve environmental performance. Researchers have attempted to map this relationship by studying the adoption of carbon pricing individually, that is carbon trading, carbon tax and internal carbon pricing have been analysed individually in literature. To the best of our knowledge, this study is the first to consider the adoption of single and multiple carbon pricing mechanisms simultaneously.

The primary research question is whether environmental performances (measured through carbon intensity, energy intensity and environmental score) improves through the adoption of carbon pricing mechanisms. The results indicate that the presence of carbon pricing mechanism significantly improve the carbon intensity and the environmental score. Further analysis show that carbon tax is the only mechanism that can improve environmental performance on its own, carbon trading and internal carbon price should be paired in order to be significant. Surprisingly, the presence of all three types of carbon pricing mechanisms do not influence environmental performance. The sample has also been split into carbon intensive firms. The results indicate that carbon pricing mechanisms adopted by high carbon intensive firms are more likely to reduce emissions and improve environmental performance. The role of environmental innovation and board members' independence as moderating variables have been uncovered. The presence of multiple carbon pricing mechanisms require a high rate of environmental innovation and strong board independence to improve the environmental performance.

This study contributes to the literature by providing new insights on the adoption of single versus multiple carbon pricing mechanisms. It has important policy implications for managers and policymakers who are facing the challenge to decarbonise and to put a price on carbon. Future research can assess the rate of carbon pricing and compare the impact on emission reductions. There is a growing trend for reporting carbon pricing rate being adopted internally by firms. In addition, the impact of adoption of carbon pricing can be measured on different measures of environmental performance beyond the emissions and overall environmental score.

	Model 1	Model 2	Model 3
CM	0.043^{*}	0.087^{***}	0.004
	(0.025)	(0.025)	(0.053)
CM*Innovation	0.000	-0.000	0.001
	(0.001)	(0.001)	(0.001)
CT	-0.075^{***}	-0.021	0.091^{**}
	(0.020)	(0.020)	(0.042)
CT*Innovation	0.001^{**}	0.000	0.000
	(0.000)	(0.000)	(0.001)
ICP	0.041	0.045^{*}	0.083
	(0.026)	(0.026)	(0.054)
ICP*Innovation	0.001	0.001	0.003^{**}
	(0.001)	(0.001)	(0.001)
CM∩CT	0.079	-0.159^{***}	0.059
	(0.058)	(0.058)	(0.121)
CM∩CT*Innovation	-0.002	0.002	-0.005
	(0.001)	(0.001)	(0.003)
CM∩ICP	0.096^{*}	-0.174^{***}	0.205^{*}
	(0.054)	(0.054)	(0.113)
CM∩ICP*Innovation	-0.003^{***}	0.003^{***}	-0.002
	(0.001)	(0.001)	(0.002)
CT∩ICP	0.006	-0.451^{***}	0.022
	(0.065)	(0.065)	(0.135)
CT∩ICP*Innovation	0.000	0.005^{***}	-0.002
	(0.001)	(0.001)	(0.002)
CM∩CT∩ICP	0.150^{***}	0.048	0.251^{**}
	(0.052)	(0.052)	(0.108)
CM∩CT∩ICP*Innovation	0.003^{***}	0.000	-0.002
	(0.001)	(0.001)	(0.002)
R^2	0.004	0.135	0.005
Adj. R^2	0.004	0.134	0.004
Num. obs.	25333	25333	25333

$^{***}p < 0.01$; $^{**}p < 0.05$; $^{*}p < 0.1$

Table 4.13: Innovation as moderating factor

	Model 1	Model 2	Model 3
CM	0.035	0.038	0.209***
	(0.031)	(0.031)	(0.064)
CM*Board Independence	0.000	0.001	0.004***
	(0.001)	(0.001)	(0.001)
CT	−0.120***	−0.022	0.203***
	(0.022)	(0.022)	(0.047)
CT*Board Independence	−0.002***	0.000	0.002***
	(0.000)	(0.000)	(0.001)
ICP	0.056*	0.184***	0.268***
	(0.030)	(0.030)	(0.063)
ICP*Board Independence	0.000	−0.003***	0.003**
	(0.001)	(0.001)	(0.001)
CM∩CT	−0.089	−0.016	−0.138
	(0.065)	(0.065)	(0.135)
CM∩CT*Board Independence	0.004***	−0.002*	0.001
	(0.001)	(0.001)	(0.003)
CM∩ICP	−0.070	−0.101*	0.262**
	(0.061)	(0.061)	(0.126)
CM∩ICP*Board Independence	0.001	0.001	−0.003
	(0.001)	(0.001)	(0.002)
CT∩ICP	0.100*	−0.225***	0.254**
	(0.060)	(0.060)	(0.126)
CT∩ICP*Board Independence	−0.002*	0.001	0.009***
	(0.001)	(0.001)	(0.003)
CM∩CT∩ICP	0.184***	0.019	0.403***
	(0.055)	(0.055)	(0.114)
CM∩CT∩ICP*Board Independence	−0.002	0.001	0.007***
	(0.001)	(0.001)	(0.003)
R^2	0.005	0.135	0.006
Adj. R^2	0.004	0.134	0.006
Num. obs.	25333	25333	25333

$^{***}p < 0.01$; $^{**}p < 0.05$; $^{*}p < 0.1$

Table 4.14: Board Independence as moderating factor

Chapter 5

Energy Prices, Stock Prices and Carbon Pricing

Article title: A Global Perspective on the Nexus Between Energy and Stock Markets in Light of the Rise of Renewable Energy

Abstract: The rise in renewable energy and the associated divestment initiatives from fossil fuel around the world have become prominent in combating climate change. This paper revisits the relationship between energy and stock markets by accounting for renewable energy through the use of the Divisia index method. We retrieve data for both the price and consumption of fossil energy (oil, coal and gas) *and* renewable energy (solar, wind and hydro) . We estimate a Vector Autoregressive (VAR) model over the period 2000-2019 across 25 countries globally. The most significant time-dependent dynamics is found between renewable energy and both the energy company stock and carbon markets, while fossil energy has no significant influence. Renewable energy has nevertheless no significant impact on the broader stock market, including the technology sector. The increasing influence of renewable energy in this nexus signals to policymakers that investors have started to shift their focus of attention from fossil to renewable energy, but this shift is still limited to the energy and carbon sectors.

Keywords: renewable energy prices, fossil energy prices, stock prices

JEL: JEL Classification: Q1, Q2, Q4, Q5

5.1 Introduction

Renewable energy has gained significant attention on the global political agenda due to the pressing issues of climate change, energy security, and increasing energy demand. Experts now universally acknowledge that renewable energy plays a crucial role in addressing these challenges. In fact, the 2019 Renewables Global Status Report reveals that renewable energy made up approximately 18.1% of the total final consumption in 2017. Furthermore, an increasing number of countries are now surpassing the 20% threshold of renewable energy in their electricity mixes, as highlighted by (Xia et al., 2019). The promising growth of the renewable energy sector, coupled with the noticeable shift away from fossil fuels, has sparked heightened enthusiasm among investors for renewable power and fuel, as noted by (Liu et al., 2021). Even developing and emerging economies are actively participating in renewable energy investment, with China leading the way by accounting for 32% of global renewable energy investment in 2018. The total investment in renewable power exceeded three times the amount invested in new gas and coal generators.

The increasing prominence of renewable energy has led to a growing interest among practitioners and academics in examining whether renewable energy prices can affect stock performance (Ferrer et al., 2018). A few studies have proposed a positive relationship between clean energy stocks and financial markets (see for e.g Henriques and Sadorsky (2008); Sadorsky (2012); Kumar et al. (2012)). This study revisits the existing literature in light of the rise of renewable energy, its impact on stock prices, including those of energy and technology companies, while considering the ongoing influence of fossil fuel energy.

The transition towards renewable energy is closely intertwined with the traditional fossil fuel sector, and fossil fuel prices have a significant influence on the development of renewable energy, particularly in terms of investments and returns. For instance, when fossil fuel prices are low, the opportunity costs of developing alternative renewable energy sources increase. This may result in decreased incentives for investors to support renewable energy production, potentially leading to lower stock prices for renewable energy companies. Conversely, when fossil fuel prices are high, incentives to explore renewable energy are stronger, leading to potential increases in stock prices for renewable energy companies. In general, we would expect to observe a negative relationship between fossil fuel prices and renewable energy stock prices. Existing empirical studies have examined the impact of fossil fuel prices, such as oil, coal, and gas, on the stock returns of clean energy companies. Some studies also suggest that other variables, such as carbon returns and technology stock returns, can also influence energy prices.(Hammoudeh et al. (2014); Henriques and Sadorsky (2008); Sadorsky (2012); Kumar et al. (2012); Qin (2014); Sun et al. (2019); Xia et al. (2019); Pham (2019), among others).

Although the investment community's alignment with climate goals holds significant practical implications, there is a dearth of literature investigating the effects of renewable energy price changes on company shares in both traditional and emerging energy sectors. As highlighted by Gallego-Álvarez et al. (2015), understanding this relationship can offer valuable insights for investors in constructing optimal investment portfolios to mitigate risks and achieve excess returns in the transition to a low-carbon economy. For instance, abrupt changes in volatility and correlation between renewable and fossil energy prices can significantly impact energy-intensive companies, incentivizing investors to identify better-positioned companies that can swiftly adapt their energy consumption levels and adopt innovative technologies, as noted by Gong et al. (2021). As renewable energy continues to gain prominence, it is imperative to evaluate the governing correlation between renewable and fossil energy prices in relation to stock returns.

Scholars have adopted different models to investigate the correlation between energy and stock market prices. For example, Lin and Li (2015) used a VEC-MGARCH model, Ji et al. (2018) use a VAR model to test the correlation in carbon-energy system whilst Kumar et al. (2012) use a VAR model to study oil prices, carbon prices and clean energy stock prices. Cong et al. (2008) examine the dynamics between oil prices shocks and the stock market using as VAR model as well. Dutta et al. (2018) adopt a VAR-GARCH model to assess the link between carbon price and clean energy stock indices. Zhang and Du (2017) develop a TVP-SV-VAR model to estimate the linkage among stock prices of new energy, high technology and fossil fuel companies.

The existing body of literature primarily focuses on examining the relationship between fossil fuel energy prices and stock returns of renewable (or clean) energy companies. However, it is equally important to consider the impact of renewable energy prices on stock returns. Furthermore, the current studies are often limited to a few countries, such as China and the US. In this paper, we adopt a global perspective and analyze data from 25 countries, encompassing renewable energy consumption and prices (including solar, wind, and hydro). Our research question revolves around investigating how changes in renewable energy prices affect overall stock performance, as well as the performance of energy companies, while controlling for other influences such as fossil fuel energy prices, carbon market prices, and correlations with stock market indices and other sectors. Specifically, we calculate renewable energy returns (RR) based on data from the OECD, and fossil fuel energy returns (FR) using data from IndexMundi for oil, coal, and natural gas commodities. We also include stock prices from broad stock indices (BSR), technology company stock indices (TSR), and energy stock indices (ESR) for each country. Additionally, we consider carbon market prices from various regional trading systems (CR) in our analysis.

Our contribution to the literature is threefold. Firstly, we incorporate a comprehensive set of energy sources, including fossil fuels (oil, gas, and coal) as well as renewable sources (solar, wind, and hydro), in our VAR model. While previous studies have used renewable company stock prices as a proxy for renewable energy prices, we utilize actual prices of renewable energy sources, which encourages further investigation into renewable energy sources. Secondly, we introduce the Divisia index method to analyze renewable energy prices, which is a novel approach that extends previous studies that have overlooked renewable energy sources (Sun et al. (2019); Choi and Oh (2014); Wang et al. (2014); Choi and Ang (2012)) . Lastly, we expand the scope of analysis to include 25 countries from 2000 to 2019, going beyond the limited focus on the US and China in earlier studies.

Our research reveals that renewable energy prices have a strong time-varying relationship with energy company stock prices. We also find that increased investment in renewable energy leads to reduced demand and increased supply of CO2 permits, resulting in lower carbon prices. These results cannot be attributed to the indirect influence of fossil energy as fossil energy does not exhibit any significant relationship with the variables we tested. This can be explained by the fact that investors account for the costs of transitioning away from fossil energy in discounted cash flow models over extended periods of time. Finally, our findings highlight that neither the broad stock market nor the technology sector is significantly influenced by renewable energy. These results are consistent across 25 countries. Renewable energy is making its own mark in financial markets, but its impact remains limited to the energy company stock and carbon markets.

The remainder of this paper is structured as follows. Section 2 in the paper reviews the related literature on the relationship between energy prices and stock markets and motivates our study from a theoretical perspective. Section

3 explains the methodology and the data. Section 4 specifies and estimates the VAR model based on stock indices, carbon prices, technology stock prices, energy stock prices, the Divisia index of fossil energy as well as the Divisia index of renewable energy. In this section, we also discuss the impulse response, Grangger causality, and variance decomposition findings. The last section concludes.

5.2 Literature Review

This section outlines the theoretical framework that governs the connection between stock and energy prices, considering the Natural Capital Theory, the stranded assets issue, and portfolio theory. It also reviews the existing empirical literature and provides rationale for our chosen methodology and selection of outcome and control variables.

5.2.1 Theoretical foundations

The relationship between renewable energy, fossil energy and stock prices that we explore in our study is governed by the substitutability condition that is conceptualised in the Natural Capital Theory (NCT). The theory explains the paradigm shift from fossil to renewable energy sources (Pearce, 1988; Costanza and Daly, 1992; Barbier, 2019; Khan et al., 2021). NCT suggests that the relationship between renewable and fossil energy is determined by how easily they can be replaced by one another. The theory argues that we can move away from non-renewable resources to renewable ones and still achieve sustainable economic development. This means that companies can use renewable natural resources like wind, solar, or hydropower and at the same time rely less on non-renewable resources like coal, oil, or gas. This is illustrated in Figure 1.

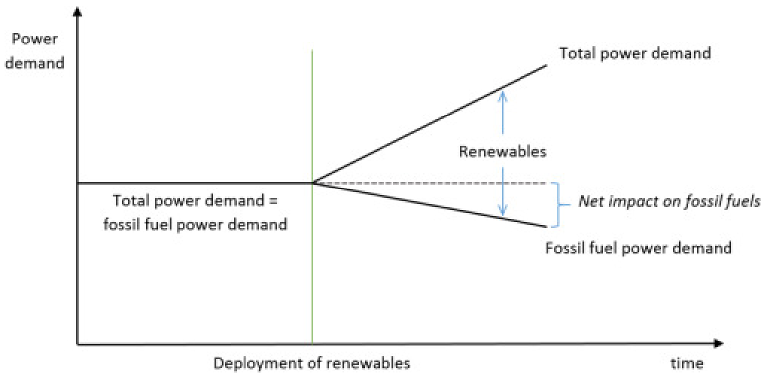

Figure 5.1: Renewable energy effect on fossil fuels
(Source: Foster et al. (2017))

It is therefore possible for companies to enhance their environmental protection efforts and promote long-term sustainability by decreasing their dependence on non-renewable resources. This can help lower their exposure to reputation and systemic risks, and consequently, make their company shares more

Another theoretical justification behind the relationship between renewable energy, fossil energy and stock prices is given by the existence of stranded assets which lose value or becomes unusable in a sudden or unexpected way. Stranded asset risk can arise through transition risk, i.e., through the implementation of carbon budgets or national and international restrictions on carbon-intensive activities (Chenet et al., 2015). Stranded assets can suffer from devaluation or conversion to liabilities (Caldecott et al., 2014). This poses a risk for investors who have invested in such assets, as they may incur significant losses. It also highlights the need for a smooth and just transition to a low-carbon economy, which involves managing the risk associated with stranded assets and ensuring that affected communities and workers are not left behind. In such an environment, energy price dynamics are clearly related to stock prices as investors are looking for ways to shift investments away from fossil fuel to renewable energy. Conversely, adequate financing mechanisms are also necessary to support the growth of renewable energy, and the stock market is a crucial avenue for funding.

Finally, whilst the just transition and divestment trend is on the rise, the Modern Portfolio Theory (Markowitz, 1968; Roy, 1952; Tobin, 1958) highlights that the constraints related to the substitution of energy sources may leave investors with a less efficient portfolio. Disinvestment would implies lower diversification benefits and more strongly correlated stock returns, leaving investors with lower risk-adjusted returns in fossil-free portfolios in comparison to unconstrained portfolios. A study by Kuang (2021) also found that clean energy stocks generally underperform the overall equity market but outperform dirty stocks. It also summarises on how diversification between clean energy and fossil fuel depends on the degree of decarbonisation and the energy sub sectors.

5.2.2 Empirical Foundations

The fundamental economic principles on which rely the three theoretical frameworks explained in the previous section clearly show that renewable and fossil energy prices are intrinsically connected to company stock prices. In the empirical studies reviewed below, we nevertheless show that evidence on the link between stock markets and energy is very much limited to fossil energy.

Kilian (2009) employs a structural VAR model to decompose the oil demand and supply shock on US stock markets. The results show no significant impact of oil supply shock on US stock markets. Apergis and Miller (2009) expand the research to eight countries and find little evidence between oil market and stock markets. Sadorsky (2012) studies the impact of oil in emerging markets and show that oil prices react positively to positive shocks on the emerging stock markets. Similarly, Fang and You (2014) assess the fossil energy impact on stock markets in China, India and Russia and find no significant effect. Chen and Li (2015) find an extreme dependence between oil prices and Chinese stock markets. Given the increasing adoption of renewable energy, it is crucial to revisit the literature and assess the impact of renewable energy on stock markets. Likewise, the influence of fossil energy on stock markets must be revisited in the presence of renewable energy. Thus, we hypothesise that an increase in energy prices would negatively impact on stock prices.

The relationship between fossil energy prices and the renewable energy companies have been previously studied. Oil price can play a central role in determining the profitability of renewable energy projects by incentivizing or discouraging the use of alternative energies. An increase in oil price can transmit negative effects on household consumption and aggregate output (through reduced household income and increased production costs), thus resulting in lower stock returns (Edelstein and Kilian, 2009). A series of studies find supporting evidence to the oil-renewable energy stocks relationship. For example, Henriques and Sadorsky (2008) study the relationship between oil prices and alternative energy stock prices using a vector regression model (VAR) and conclude that oil prices can Granger cause them. Dutta (2017) find similar results by using a volatility index in the international crude oil markets. Reboredo (2015) uses copula models to measure the dependence between oil prices and renewable energy stock prices and concludes that oil prices can significantly influence the downside and upside risks of renewable energy stock returns. Pham (2019) finds heterogeneous relationship between the two variables and also indicates that it differs across sub-sectors. Broadstock et al. (2012) and Wen et al. (2014) document mean and volatility spillover effects between renewable energy and fossil fuel companies in China. However, Ferrer et al. (2018) find no significant influence from crude oil prices to renewable energy stock prices. Investment risks in renewable energy markets are also higher than in traditional energy industries and they face speculative behaviours (Bohl et al., 2013).

Another strand of the literature has analysed the relationship between various energy prices on the development of renewable energy. Kumar et al. (2012)

study the nexus between carbon prices, clean energy stock prices and oil prices using a VAR model. They conclude that oil prices can affect the stock prices of clean energy firms while carbon prices fail to do so. Sun et al. (2019) use the Divisia price synthesis method on prices of coal, oil and natural gas to investigate the effect of fossil energy prices on new energy stock prices. Their results demonstrate that new energy stock prices are mainly affected by lagged values while the effects of fossil energy prices are weak. Gu et al. (2020) assess the co-movements between steam coal and clean energy stocks in China using a VAR-DCC-GARCH framework for the period 2008 to 2019 and indicate the presence of significant bi-directional volatility between the variables. Zhang and Du (2017) employ a coal-oil index as an aggregated indicator against stock prices of public companies in China and study its impact on clean energy stocks. The demand and supply of coal directly affect the investment in clean energy sources. Qin (2014) found that new clean energy stock prices are not impacted by oil and technology stock prices whilst is positively influenced by coal and carbon prices.

Carbon prices are deemed to relate to both economic activity and fuel prices (Redmond and Convery, 2006; Chèze et al., 2009; Hammoudeh et al., 2014). This relationship can be extrapolated through the fact that the consumption of fossil energy results in carbon emissions. Thus, changes in fossil energy prices affect energy consumption and consequently the demand for carbon emissions (Wu et al., 2020). Dowds et al. (2013) highlight that an increase in carbon price shifts fuel energy consumption from coal to natural gas due to the change in marginal fuel costs for electricity generation. Narayan and Sharma (2015) stipulate that carbon assets, and more specifically carbon futures, are used as a tool for portfolio diversification in order to facilitate risk mitigation and transfer.

Very few studies have assessed the impact of carbon prices on stock indices

(Oberndorfer, 2009; Kumar et al., 2012; Luo and Wu, 2016). Jiang et al. (2020) use wavelet methodology to map the time frequency connectedness between coal, new energy stock, and carbon prices in China. The findings show that carbon as well as coal price connectedness occur in both lower and higher frequency while connectedness in new energy stock prices takes place in the middle frequency. This is supported by Marimoutou and Soury (2015); Gronwald et al. (2011a); Mansanet-Bataller et al. (2007) who find similar fluctuations between the variables over time. Dutta et al. (2018) highlight through a VAR-GARCH model that EUA carbon prices can boost renewable stock returns. Ji et al. (2018) find that brent crude oil prices can significantly affect carbon prices and risks. Chevallier (2011a) find that coal prices can significantly impact on carbon prices. Regarding cap and trade regulations, Bushnell et al. (2013) find that they cause a reduction in stock prices of carbon and electricity intensive companies. Jong et al. (2014) find a negative relationship between equity prices and carbon prices, especially in case of lower carbon intensive holdings. Moreno and da Silva (2016) highlight that the European carbon price negatively impact equity returns in Spain during Phase III.

The stock prices of technology companies appear to be highly correlated with those of alternative energy companies and the price of fossil fuel (Henriques and Sadorsky, 2008; Managi and Okimoto, 2013; Kumar et al., 2012; Bondia et al., 2016; Inchauspe et al., 2015). Sadorsky (2012) finds that clean energy stock prices have stronger correlations with technology stock prices rather than oil prices. Managi and Okimoto (2013) investigate the dynamics between oil prices, interest rates, clean energy and technology stock prices using a structural break in late 2007. Their results show that both oil prices and technology stock prices have positive influence on renewable energy stock prices. These findings are supported by Bondia et al. (2016). Such correlation is fostered through the transition to low carbon economy, which has directed capital investment into innovative technology. Investors might also view renewable energy sector similar to technology sector given the need for similar resources such as research facilities, prominent engineers, thermoelectric materials and integrated circuits (Zhang and Du, 2017). The hypothesis is that a rise technological stock prices positively impact on renewable energy prices and stock prices.

Table 5.1 positions our study in the existing literature. Whilst the impact of fossil fuel prices on stock prices as well as on renewable energy sector have been extensively studied, there is scant literature on how renewable energy prices influence stock prices.

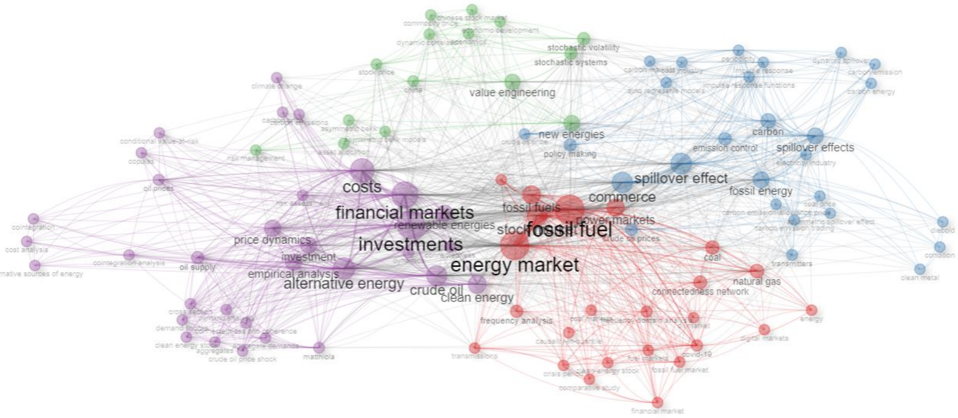

Figure 5.2: Bibliometric mapping of literature

The gap in literature is further highlighted by Figure 5.2 which shows that there is increasing interest in fossil energy markets and financial markets but the studies do not involve renewable energy. Further, variables such as carbon prices and innovation have been included in past studies. By studying fossil fuel and renewable energy prices in 25 countries while accounting for their consumption through the Divisia index by Sun et al. (2019), this paper sheds light on the nexus between those energy and stocks in a comprehensive way. Both renewable and fossil energy are considered and special attention is given to technology and energy intensive stocks, as well as carbon allowances.

Table 5.1: Positioning of our study in the literature

Authors (year)	Comparison of variables	Comparison of results
Henriques and Sadorsky (2008)	new energy stock prices, technology stock prices, oil prices and interest rate	Oil prices impact on new energy stock prices is not as effective as technology stock prices
Kumar et al. (2012)	new energy stock prices, technology stock prices, oil prices, oil prices, carbon prices and short term interest rate	technology stock prices influence new energy stock more than oil prices
Sadorsky (2012)	new energy stock prices, technology stock prices and oil prices	There is a higher correlation between technology and energy stock prices than with oil prices
Managi and Okimoto (2013)	clean energy stock prices, technology stock prices and oil prices	There is a positive relationship between oil prices and clean energy prices. A similarity between clean energy stock prices and high-tech stock prices is also suggested
Qin (2014)	new energy stock prices, technology stock prices, coal prices, oil prices and carbon prices	new energy stock prices are not impacted by oil and technology stock prices whilst is positively influenced by coal and carbon prices
Zhang and Du (2017)	new energy stock prices, technology stock prices, coal-oil price index	new energy stock prices correlate more highly with technology stock prices than with coal and oil prices
Sun et al. (2019)	new energy stock prices, technology stock prices, carbon prices, Divisia energy price index	the correlation between new energy stock and technology index is more significant than with Divisia fossil energy price index
Nasreen et al. (2020)	clean energy stock prices, technology stock prices, oil prices	technology stocks seem to lead oil prices and clean energy stock returns. Significant relationship noted between oil prices and clean energy stock returns for the period 2006-2009.
This study	Divisia fossil energy price, Divisia Renewable energy price, stock indices, carbon prices, technology stock prices, energy stock prices	renewable energy prices correlated to energy stock prices and carbon prices. Technology stock prices influence carbon prices and stock indices whilst carbon prices impact on stock indices, renewable energy and energy stock prices

5.3 Data and Methodology

5.3.1 Data

The data set includes six time series, namely renewable energy prices, fossil fuel prices , carbon prices, broad stock index prices, technology company stock prices, and energy company stocks prices. The data set covers the period from 2000 to 2019 at the annual frequency for around 25 countries.

We had to use annual data since the consumption of renewable and fossil fuel energy is reported on an annual basis. The consumption data has been retrieved from the International Energy Agency (IEA) that reports on energy consumption data. The list of 25 countries in our sample stems from the IEA countries whose data is reported and available publicly. As shown Appendix C, the list includes both developed and developing countries, although data availability skews the sample towards developed countries.

First, unlike previous studies which use clean energy stocks as a proxy for renewable energy, we directly estimate the renewable energy prices for each country from the renewable energy tariffs reported annually and made publicly available by the OECD.

Second, for fossil fuels (namely oil, coal and natural gas), we extract data from the IndexMundi website. The Brent Crude oil is used as representative for oil prices, South Africa's coal for coal prices, and Henry Hub Natural Gas for natural gas.

Third, daily carbon prices have been downloaded from ICAP and then annualised. Given carbon markets have mushroomed around the world and are nowadays deemed as key financial initiatives to combat climate change, we can use carbon prices based upon the geographical location of each country in our

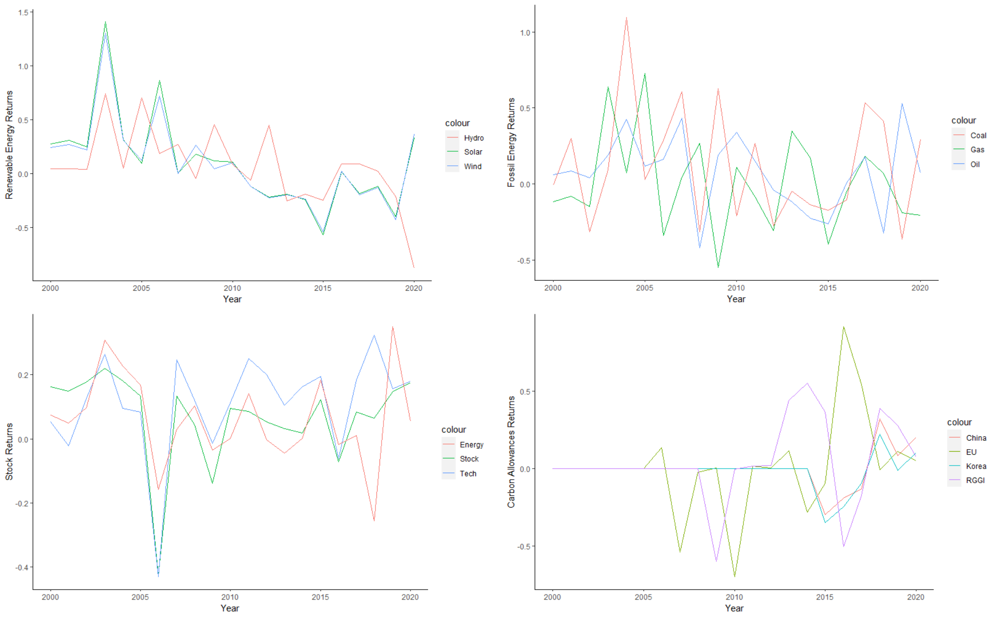

Figure 5.3: Annual Return Trend of Variables

sample, i.e, EU countries have been allocated the EU carbon price, North and South American countries have been attributed the RGGI carbon price and Asian countries have received the Chinese carbon price. However, emission trading systems were only implemented as from 2008.

Finally, we retrieve data on stock prices from Refinitiv. For each country, we use three stock indices: a broad stock index, an energy stock index, and a technology stock index. They are all listed in Appendix C. Figure 5.3 presents the trend of renewable energy price returns, fossil energy price returns, the different stock returns (broad stocks, technology stocks and energy stocks) as well as the carbon allowances returns from different emission trading systems. The annual trend has been calculated on the average value for each variable.

5.3.2 Divisia Index

The Divisia index was first proposed by Boyd et al. (1987) and has been favored in energy-related studies. Kim et al. (2020a) use a decomposed Divisia index to study the factors influencing carbon emission and electricity generation. Similarly, Chapman et al. (2018) adopt the Logarithmic Mean Divisia Index (LDMI) to identify the main contributing changes in carbon emissions in six Northeast Asian countries. Zhou et al. (2017) also assess the drivers of carbon emissions in Chinese regions. While the above studies use the Divisia index to decompose the changes in energy structure, emission factor, energy intensity and renewable energy has never been accounted for. To fill this gap and uncover the relationship between renewable energy prices and stock prices while controlling for the other energy sources, we use the Divisia index synthesis method adopted by Sun et al. (2019) to obtain the Divisia renewable energy price index based on the prices and consumption for renewable energy, namely solar, wind and hydro. We follow the same method to estimate the Divisia fossil energy price index based on fossil energy, namely oil, gas and coal.

For these two Divisia indexes, we calculate the logarithmic percentage, r_t, in the following way:

$$r_t = 100[ln(P_t) - ln(P_{t-1})] = 100[\sum_i 0.5(s_{it} + s_{it-1})(ln(p_{it}) - ln(p_{it-1}))] \quad (5.1)$$

where $s_{it} = \frac{p_{it}x_{it}}{\sum_i p_{it}x_{it}}$, p_{it} represents the unit price of the energy source i in year t, x_{it} indicates the consumption of the energy source i in year t, and P_t represents the Divisia index price in year t. We therefore obtain two time series of log percentages for renewable energies and fossil fuels, respectively the RR and FR variables.

5.3.3 Log percentages

For the other four time series, we compute the log percentages, r_t, also called log returns, in the traditional way where $r_t = 100[ln(P_t) - ln(P_{t-1})]$ and P_t is the price at time t.

We therefore obtain the broad stock index log returns (BSR), the log percentages of carbon emission prices (CR) prevailing on the different carbon markets (EU ETS, California ETS, Quebec ETS, Chinese Pilot ETS and South Korean ETS), the technology stock index log returns (TSR), and the energy stock index log returns (ESR).

5.3.4 Descriptive Statistics

In Table 5.2, it can be inferred that the mean across countries and time are negative for both renewable energy and fossil fuel prices. Fossil fuel prices have a smaller negative return than renewable energy prices. All the three stock indices display positive mean return. As expected, the technology stock index (TSR) performs the best, followed by the broad stock index (BSR) and the energy stock index (ESR). Carbon emission returns also maintain a positive momentum.

Table 5.2: Descriptive Statistics of Variables

Variable	RR	FR	BSR	CR	TSR	ESR
Mean	-0.1697	-0.0043	0.0608	0.0047	0.0719	0.0215
Median	0	0	0.0912	0	0.0187	0
S.D	4.3935	0.3592	0.2534	0.2968	0.2906	0.8249
Kurtosis	59.0051	277.988	6.7213	6.2635	6.5549	188.24
Skewness	0.7518	-14.8272	-1.1825	0.5829	-0.5889	0.0023
Minimum	-42.5363	-6.7924	-1.0773	-0.8958	-1.4521	-11.946
Maximum	43.0514	1.6046	0.9614	1.0357	1.1983	11.990
Obs	473	473	473	473	473	473

The standard deviation represents the degree to which the sample sequence deviates from the mean of the sample. The smaller the standard deviation, the more concentrated the sample sequence. The volatility in fossil energy prices are more stable than renewable energy prices. Energy stock prices are less volatile than stock prices and technology stock prices.

5.3.5 Methodology

Various methods have been used in the existing literature on energy to assess the relationship amongst the variables described above. Given the prevalent endogeneity issue, we propose to use a Vector Auto Regression (VAR) model. In a VAR, each variable is treated as endogenous and depends on the lagged values of all the selected variables to correct for the presence of endogeneity (Tseng, 2017). Interestingly, the strengths of using VAR in energy prices have been confirmed by Henriques and Sadorsky (2008); Kumar et al. (2012); Kilian and Murphy (2012); Baumeister and Peersman (2013).

The general specification of our VAR model with lag p order is as follows:

$$Y_t = \phi_t Y_t + ... + \phi_p Y_{t-p} + Hx_t + \xi_t, \tag{5.2}$$

where $t = 1.2, ...T$, Y_t stands for the column vector of the k-dimensional endogenous variable, x_t is the column vector of the d-dimensional exogenous variable (including the intercept), p is the lag order, T is the total number of samples, $\phi_1, ...\phi_p$ is the dimension of $k * k$ dimension matrix to be evaluated, H is $k * d$ dimensional matrix of estimated coefficients and ξ_t is k-dimensional random perturbation column vector. Random perturbation can be linked to each other in the same period but is not linked to their own lag value or to the variables on the right side of the equation.

As indicated in the previous sections, we use annual data to investigate the relationship among renewable energy log returns (RR), fossil energy log returns (FR), carbon log returns (CR), broad stock index log returns (BSR), energy stock index log returns *(ESR)*, and technology stock index log returns (TSR). Thus, our VAR model at the country level includes 6 equations and is described as follows:

$$\begin{pmatrix} BSR \\ RR \\ FR \\ CR \\ TSR \\ ESR \end{pmatrix}_t = A_1 \begin{pmatrix} BSR \\ RR \\ FR \\ CR \\ TSR \\ ESR \end{pmatrix}_{t-1} + A_2 \begin{pmatrix} BSR \\ RR \\ FR \\ CR \\ TSR \\ ESR \end{pmatrix}_{t-2} + ... + C + \xi_t, t = 1, 2, ..., T \quad (5.3)$$

where C is a column vector of intercepts and ξ_t is k-dimensional random perturbation column vector.

5.4 Empirical Findings

We first specify and estimate the VAR model based on the six above-mentioned time series of log percentages. We then explore the relationship using impulse response functions.

5.4.1 VAR Model Specification

Before applying the VAR model, we must determine the appropriate model specification by identifying the order of integration of each data series, the existence of cointegration among the six variables, and the lag order in the system of equations.

If the variables have a unit root, it is best to take the first difference in order to make the series stationary. In addition, if there is a cointegrating relationship in the system, we should use the vector error correction model rather than the VAR model in the first differences. We therefore conduct the unit root and cointegration tests and summarize the results below.

Prior to estimating the VAR model, we compute the Augmented Dickey-Fuller (ADF) and Kwiatkowski Phillips Schmidt Shin (KPSS) unit root tests in accordance to Henriques and Sadorsky (2008); Sun et al. (2019). The null hypothesis for the ADF test is that the data series has a unit root whereas the null hypothesis for the KPSS test is that the data series is stationary.

Table 5.3: Unit Root Test

Variables	ADF	KPSS
RR	-8.1945***	0.104
FR	-8.1462***	0.153
BSR	-7.7161***	0.242
CR	-9.7738***	0.047
TSR	-7.1426***	0.786
ESR	-6.4843***	0.153

ADF and KPSS tests have been carried out for all the six variables in the model.[1] There is no evidence of unit roots in the data, so the log percentages are stationary.

The cointegration test has been carried in line with Johansen et al. (1992) in the context of the following $k = 6$ dimensional vector autoregression model:

$$y_t = \sum_{i-1}^{k} \phi_i y_{t-i} + \mu + \mu_t, \tag{5.4}$$

where y_t are the time series of prices for the six variables, and μ_t is an independently and identically distributed p-dimensional vector with a zero mean and a covariance matrix.

We use both trace and maximum eigenvalue statistics to test for the number of cointegrating vectors. The results in Table 5.4 show that the null hypothesis that there was no co-integration relationship at the significance level of 5%, is not rejected in both cases. Therefore, there was no long-term equilibrium

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[1] ***, ** and * denotes statistical significance at 1%, 5% and 10% level respectively.

relationship among the six variables in this model.

Table 5.4: Unintegrated Cointegration Rank Test

	Eigen Value	Trace Stats	Critical Value	Max Eigen Value	Critical Value
0	0.421	673.39	102.14	271.92	40.30
1	0.321	401.47	76.07	192.29	34.40
2	0.241	209.18	53.12	136.52	28.14
3	0.067	72.66	34.91	34.62	22.00
4	0.044	38.04	19.96	22.61	15.67
5	0.030	15.42	9.24	15.42	9.24

There is a trade-off to determine the lag order in a VAR model. On the one hand, p should be large enough to reflect the dynamics in the model. On the other hand, the greater the lag order, the more parameters need to be estimated which eventually results in lower degrees of freedom. The lag order can be determined using various methods (Runkle, 1987). When the Akaike information Criterion (AIC), Schwarz's Criterion (SC) or Hannan-Quinn's Criterion (HQ) do not lead to the same lag order, the lag order is usually set by relying on the SC which embodies a stiffer penalty, in line with Tang and Aruga (2021). As shown in Table 5.5, the lag is set equal to 2. This is also confirmed by the final prediction error (FPE).

Table 5.5: Lag length selection for VAR model

Lag	AIC	HQ	SC	FPE	LR	LogL
1	-2.723565e+01	-2.708789e+01	-2.686031e+01	1.484956e-12	NA	2415.44
2	-2.764352e+01	-2.736910e+01	**-2.694645e+01**	**9.876703e-13**	0.15	2523.82
3	-2.770590e+01	-2.730482e+01	-2.668710e+01	9.281172e-13	0.21	2563.51
4	-2.787645e+01	-2.734872e+01	-2.653593e+01	7.828660e-13	0.39	2617.96
5	-2.792497e+01	-2.727059e+01	-2.626273e+01	7.462156e-13	0.43	2650.53
6	-2.820827e+01	**-2.742724e+01**	-2.622430e+01	5.625938e-13	0.42	2747.61
7	-2.819146e+01	-2.728378e+01	-2.588578e+01	5.727982e-13	0.39	2768.92
8	-2.813633e+01	-2.710199e+01	-2.550892e+01	6.062055e-13	0.31	2786.57
9	**-2.825184e+01**	-2.709085e+01	-2.530271e+01	5.411488e-13	0.32	2838.57
10	-2.821622e+01	-2.692857e+01	-2.494536e+01	5.621696e-13	0.06	2956.24

The figures in bold represents the lag order selected by the criterion. AIC is the Akaike Information Criterion, HQ represents Hannan-Quinn information criterion, SC is the Schwarz Information Criterion, FPE represents Final prediction error, LR is the Likelihood ratio test and LogL is the Loglikelihood test.

5.4.2 VAR Model Estimation

As explained in the previous sections, the VAR model reported in Table 5.6 has been generated with an optimal lag order of 2.[2]

Table 5.6: VAR Results

Variables	RR	FR	BSR	CR	TSR	ESR
RR(L1)	0.9211***	-2.52e-03	-0.0996	0.0049	-0.3694	2.1219**
FR(L1)	0.1316	0.0340***	-1.5523	1.4701	-4.3291	-1.1609
BSR(L1)	-0.0024	0.0006	-0.1383**	0.1091*	-0.1858***	0.0884
CR(L1)	-0.0056	4.536e-05	0.0534	0.2083***	0.1011**	0.0189
TSR(L1)	-0.0067	-0.0006	0.0641	-0.0098	-0.0163	0.0487
ESR(L1)	0.0209***	-0.0003	-0.0288	-0.0199	-0.0437*	-0.7601***
RR(L2)	-0.4562***	0.0015	0.0481	-0.9527**	0.0333	-1.5516
FR(L2)	0.0349	-0.0307***	-2.7544	-3.6064	-3.9423	-6.8697
BSR(L2)	-0.0005	0.0010	-0.0320	0.1218**	-0.0568	-0.0990
CR(L2)	-0.0046	-1.060e-05	0.0605	-0.1692***	-0.0185	0.1743
TSR(L2)	-0.0094	-0.0002	0.0857*	0.0251	0.0603	0.1139
ESR(L2)	0.0055	0.0005	0.0124	0.0963*	-0.0121	0.0151
Observations	473	473	473	473	473	473
R^2	0.474	0.1629	0.03849	0.1217	0.06172	0.3662
$Adjusted R^2$	0.4602	0.141	0.01335	0.09871	0.03719	0.3496
F-Stats	34.46***	7.442***	1.531*	5.298***	2.516***	22.1***

***, ** and * denotes statistical significance at 1%, 5% and 10% level respectively.

To the best of our knowledge, this study is the first to identify a bidirectional dynamic link between renewable energy (RR) and energy stocks (ESR). First, renewable energy log returns are positively influenced by past energy stock log returns, as indicated in the first column of Table 5.6. When the market capitalization of energy companies increases and there is positive momentum in the sector, these companies have more likely to shift towards renewable energy and make it more valuable. Second, renewable energy log returns (RR) positively influence energy stock log returns (ESR), as indicated in the last column of Table 5.6. This causal relationship can be explained by the greater reliance of energy companies towards cleaner energy sources following the many divestment initiatives from fossil fuel taken globally, especially in the energy sector

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[2] To test the robustness of this pooled VAR model, we have also run the fixed Panel VAR and GMM Panel VAR models. No significant differences were detected.

(Renewable-Energy, 2019). This divestment by energy companies is driven by greater stranded asset risks, i.e, the risk of obsolescence for infrastructures built up around fossil fuels (Curtin et al., 2019). In a low carbon transition regime, impeding danger of stranded assets leads to unburnable carbon, implying that fossil fuel energy sources cannot be burned if the world is to adhere to any given temperature outcome. In these circumstances, the value of fossil energy decreases and fails to have positive return (Caldecott et al., 2014) while it becomes more profitable for energy companies to adopt sources of cleaner energy whose worth therefore tends to rise. Renewable energy is also dynamically related to carbon emission allowances in the VAR model. Increasing renewable energy prices motivate energy companies to increase investment in clean energy. Given that energy-intensive companies rely on emission trading systems extensively, the resulting divestment from fossil fuel leads to a decrease in demand for CO2 allowances, pushing carbon prices down (Akram et al., 2020). Finally, renewable energy displays correlated log returns over time (up to lag 2) and is not relalted to fossil energy log returns (FR), broad (BSR) and tech stock log returns (TSR).

Fossil energy displays weaker interplay in the VAR model than renewable energy. There is no significant relationship between fossil fuel and renewable energy, carbon allowances, or even stock returns. This result is in accordance with Kilian (2009); Inchauspe et al. (2015); Sadorsky (2012); Fang and You (2014) who find little to no evidence of significant impact of fossil energy on stock markets. Existing studies by Ferrer et al. (2018) and Nasreen et al. (2020) find little evidence of connectedness between fossil energy and clean energy stock returns. The insignificant relationship between fossil and renewable energy represents the decoupling of the renewable energy market from the conventional energy market (Umar et al., 2022). Investors in conventional energy may aim to maximise their welfare at a different investment horizon than those who engage in low carbon transition projects. Also, the insignificant influence of fossil fuel on company stock returns might rest on factors such as the investment horizon, the ease of exit, discounted cash flow methods, and ownership of remaining reserves, as put forward by Shimbar (2021). Regarding discounted cash flow models used in corporate finance, they forecast cash flows over many years, typically assuming a smooth market transition thereby decreasing the relationship between fossil fuel shocks and stock market shocks. Also, Heede and Oreskes (2016) find that investor-owned oil, gas, and coal companies hold reserves accounting for only 16% of the remaining carbon budget, meaning that most of the risk of value destruction due to the clean energy transition is faced by countries which hold large state-owned reserves, such as Iran, Iraq, and Saudi Arabia. Therefore, private investors may question the climate commitments from countries due to their high dependence on fossil fuel revenues, anticipating no stringent climate policy to mobilize investor-owned companies and stop them from exploiting their carbon reserves. The stock prices of private companies would therefore be rather immune from changes in fossil fuel prices.

Another finding is the impact that past energy stock returns have on technology stock returns and carbon, with a lag of one and two orders respectively. The level of significance remains rather weak nevertheless, at 10% only. First, our results would suggest that more prosperous energy companies (through higher stock returns) tend to lead to a rise in carbon prices, possibly because they keep expanding without reducing their carbon emissions enough to prevent carbon prices from rising. Second, our analysis points to a negative influence of energy stocks on technology stocks, contrary to Kumar et al. (2012). As explained by Perez (2010), energy intensive companies are motivated to innovate and invest in technology when they face a greater risk of asset impairment. When energy stock returns increase, energy companies prosper and are therefore less exposed to such a risk. In these circumstances, they are less likely to invest in technological innovation, negatively affecting technology stock companies in turn.

The discussion above can also be generalized at the broader stock market level since we identify a positive time-dependent relationship between broad stock index and carbon price changes, in line with Jiménez-Rodríguez (2019). A bullish trend in stock market prices is typically associated with booming economic activities, thereby increasing carbon emissions and ultimately raising carbon prices.

Finally, looking at time-dependent causal relationships not directly related to energy, our analysis points to a specific price dynamics between technology intensive companies and broad stock index returns. First, when broad stock index prices are lifted by new capital injection, it leads to downward pressure in the prices of tech-intensive companies later. When limited or scarce capital is invested in the broader economy without first prioritizing the tech sector, the tech-intensive company stocks are hurt subsequently due to insufficient new capital injection. Second, when technology-intensive companies become more prosperous in the first place (through higher stock returns), this benefits the whole market later (at a 10% significance level and with a lag order equal to 2). Capital investment in technology is indeed deemed as a risk reduction indicator leading investors to broaden their investment base in the markets. These findings are in accordance with the literature. Similar correlations between technology stocks and developed or energy markets are observed in the literature (Henriques and Sadorsky, 2008; Managi and Okimoto, 2013; Kumar et al., 2012; Bondia et al., 2016).

5.4.3 Impulse Responses

In order to investigate the dynamic responses of energy from shocks in stocks (and conversely), we use impulse response functions. These functions showcase the effect of adding a standard deviation magnitude on the error term to the current and future values of the endogenous variable. We use a bootstrap of 1000 runs with a 95% confidence interval (in dotted red lines on the following figures).

Impulse Responses of Renewable Energy Prices

Figure 5.4 depicts the responses of renewable energy prices to changes in fossil energy prices, broad stock index market rices, carbon prices, technology stocks, and energy stock prices over the next 10 periods of time.

The most insightful result is given by the impulse response function of renewable energy prices to energy stock prices. There is a sharp and statistically significant upward trend followed by a reversal move which takes three periods of time to counterbalance the initial shock. This confirms our previous findings. When the market capitalization of energy companies increases, these companies thrive and are more likely to shift towards renewable energy and make it more valuable.

Contrary to energy stocks, the influence of fossil energy on renewable energy is very negligible, as indicated in Figure 5.2. The impulse response exhibits no trend and fluctuates very closely around zero. Contrary to Zhang and Du (2017), we do not find a strong level of interdependence between clean energy and fossil energy. There seems to be no trade-off between fossil and renewable energy prices, their dynamics being weakly interdependent. This would suggest that investments in renewable energy would be structural and not driven by opportunistic arbitrage strategies related to the level of fossil energy prices in the short run.

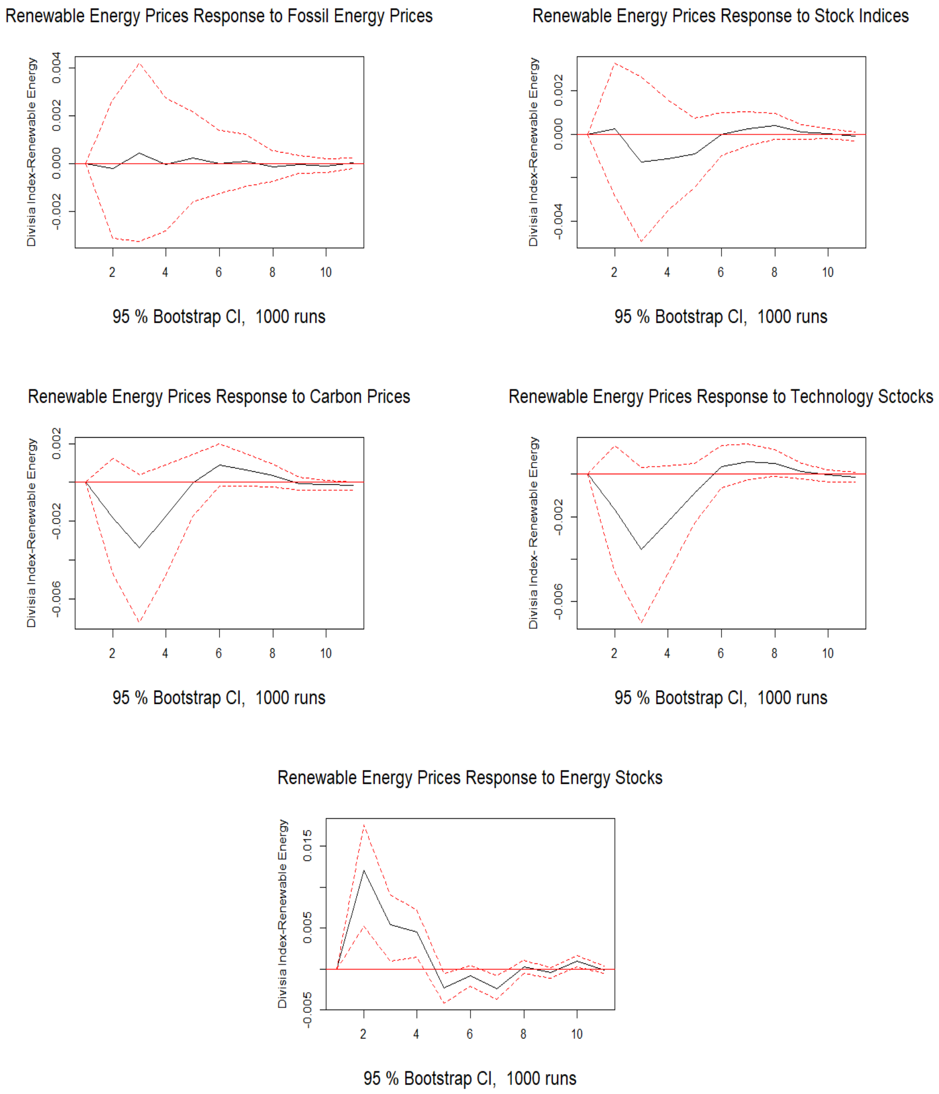

Figure 5.4: Renewable Energy Impulse Response Functions

Shocks in broad stock index prices do not much impact on renewable energy prices over time. A rather short-lived downward trend is observed, but the transition to low carbon energy sources does not seem to be much exposed to market conditions. This probably comes from the lack of market integration related to the feed-in tariffs schemes designed by national governments to promote the uptake of renewable and low-carbon electricity generation (Tietjen et al., 2016).

Although a rise in carbon prices may lead to an increase in demand for renewable energy, fuelling price hikes in the short run, we do not observe this chain of events in our impulse response function of renewable energy prices to carbon prices. Overall, the response is short-lived and not statistically significant.

The existing literature on clean energy underlines the important role that technology companies play. Although our results indicates an immediate downward trend, the reversal is quick and the response is never statistically significant.

Impulse Responses of Broad Stock Market Indexes

Figure 5.5 depicts the responses of the broad stock index prices to changes in renewable and fossil energy prices, carbon prices, technology, and energy stock prices over the next 10 periods.

Stock indices have fluctuating responses to renewable energy prices and these responses remain largely uncertain, with large confidence intervals encompassing the zero response value over time. The same pattern is identified in the case of shocks in energy stock prices. Interestingly, this is not fossil energy but renewable energy which makes the link between higher energy prices, higher energy stocks, and higher broad stock market index prices.

Overall, we cannot reject the null that the responses of stock index prices to shocks in the system are not statistically different from zero, except maybe in the case of shocks in energy stock prices, but still by a very low margin and only in some time periods.

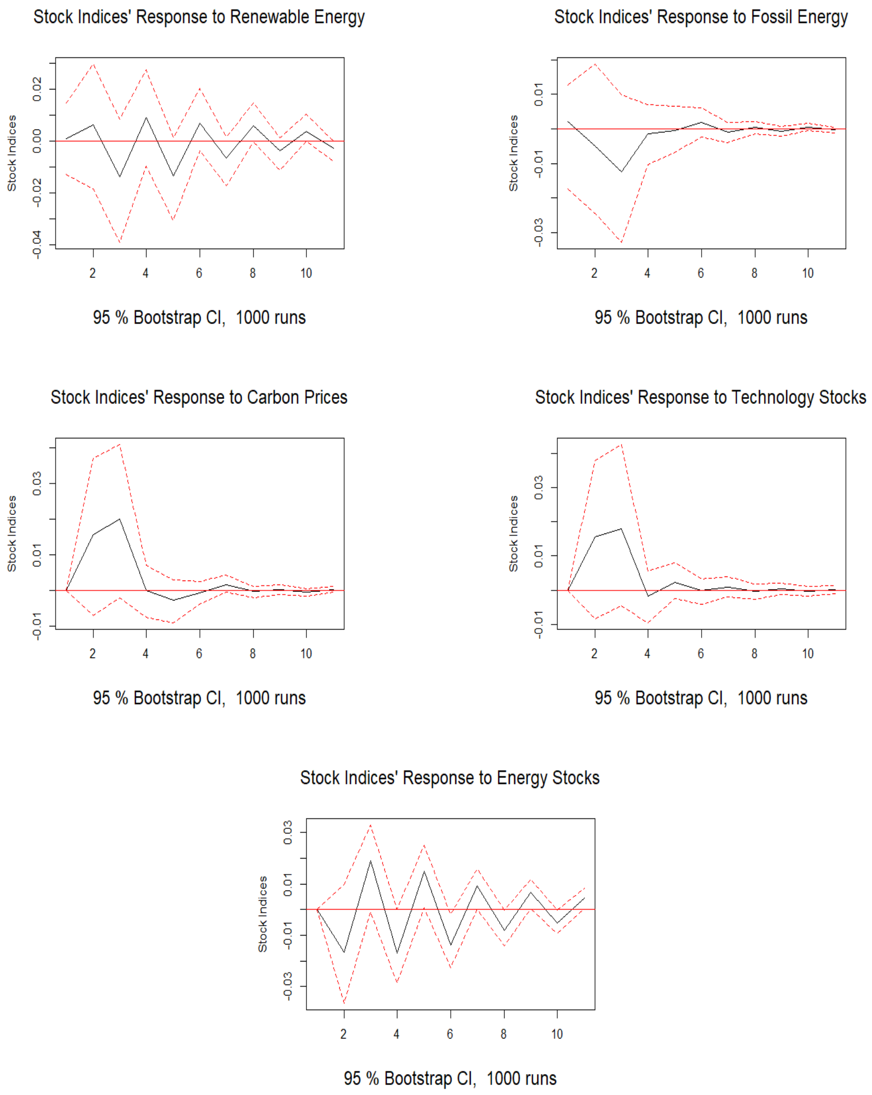

Figure 5.5: Stock Indices Response

The one standard deviation shock in fossil energy prices has a rather limited immediate effect on stock indices. Similar delayed and short lasting impacts have been found by Apergis and Miller (2009); Kilian (2009); Fang and You (2014). An increase in fossil energy can nevertheless lower gross profit margins and eventually depress stock returns, although such an effect can be mitigated by the pricing power of firms which are then able to move the inflationary pressure on their customers and remain largely unaffected.

Broad stock index prices respond quite strongly to shocks in carbon and technology stock prices over the next two periods of time, with the response fading away afterwards. Regarding carbon price changes, this maybe due to the fact they change the economic incentives of companies, which are then priced in the stock market broadly defined (Moreno and da Silva, 2016; Jiménez-Rodríguez, 2019). As to one standard deviation positive shocks in technology stock prices, they are also transmitted to the broad stock index prices at least over the next two periods of time into the future.

Impulse Responses of Fossil Energy Prices

The fossil energy prices response to renewable energy price fluctuates over time and takes longer to converge (Figure 5.4). According to Ueckerdt et al. (2013), the cost of of renewable energy relative to fossil energy matters, but it is controversial to determine how precisely the cost of renewable is accounted for. The use of leverage cost of electricity as a metric for renewable energy might lead to disparity and ambiguity in the measurement of the time dependence between renewable and fossil energies since market prices are instead used for fossil energy.

There is no statistically significant trend in the response of fossil energy prices to shocks in broad stock index prices. Although an increase in fossil energy prices lead to a rise in production costs and eventually reduces the returns (Gomez-Gonzalez et al., 2021), there is no clear evidence of an inverse dynamics from stock indices to fossil energy over time in our results. As in (Demirer et al., 2020; Dutta, 2017), we confirm the traditional view in the literature, that considers fossil fuel prices to be exogenous.

Regarding the shock effect of carbon prices on fossil energy prices, we can conjecture that carbon prices impact the power generation costs and switching costs to marginal low carbon energy. When there is an increase in carbon

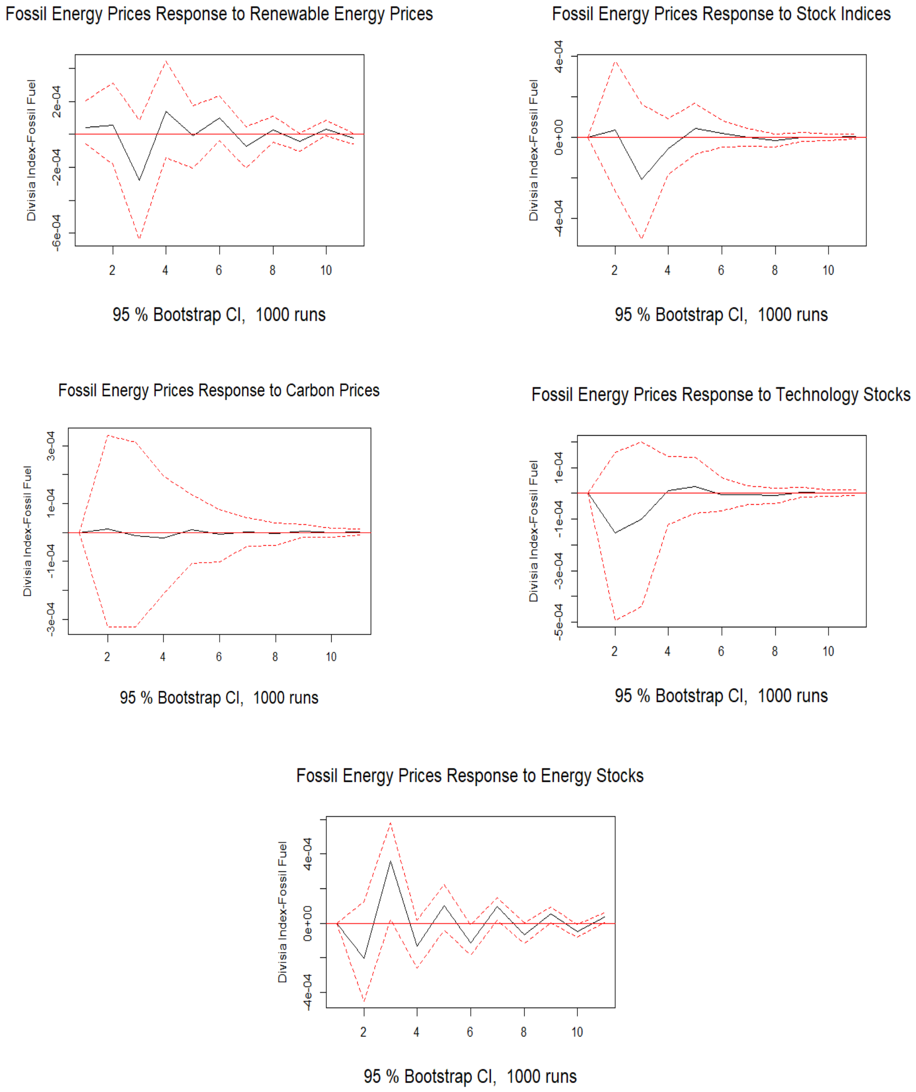

Figure 5.6: Divisia Fossil Energy Response

prices, especially when the marginal conversion cost is lower than the original cost of power generation, the demand for fossil energy from businesses decreases and ultimately the price of fossil energy falls. In our analysis, there is no obvious time varying effect of carbon prices on fossil energy prices at the annual frequency. Interestingly, Gong et al. (2021) finds that there is a spillover effect of carbon prices on oil and natural gas, but not on coal prices. Since we merge the three sources of energy in the Divisia index, the disconnection between coal and carbon may explain the lack of significance in our results.

Fossil energy prices react negatively to positive increases in technology stock prices, but the variation is not significant and remains limited. This is in line with Kumar et al. (2012) who find that technology stock prices have an insignificant impact on oil prices.

Impulse Response of Energy Stocks

The impulse responses of energy stocks take longer to converge overall, as shown in Figure 5.6. The responses are also highly fluctuating over the periods.

Energy stocks do react to renewable energy prices, with significant variations over time. In an era of international climate agreements and increasing divestment from fossil fuel, energy companies face greater regulatory risks and are increasingly sensitive to variations in renewable energy prices.

Relative to renewable energy, shocks in fossil energy prices does not lead to significant variations in energy company stock prices since the confidence interval always includes the zero value. The degree of convergence is also less obvious. The results are in accordance with Henriques and Sadorsky (2008); Zhang and Du (2017); Sun et al. (2019) who find that the correlation between the price of fossil fuel and energy stock prices is low or insignificant.

Shocks in carbon prices lead to a short-lived positive reaction in energy stock

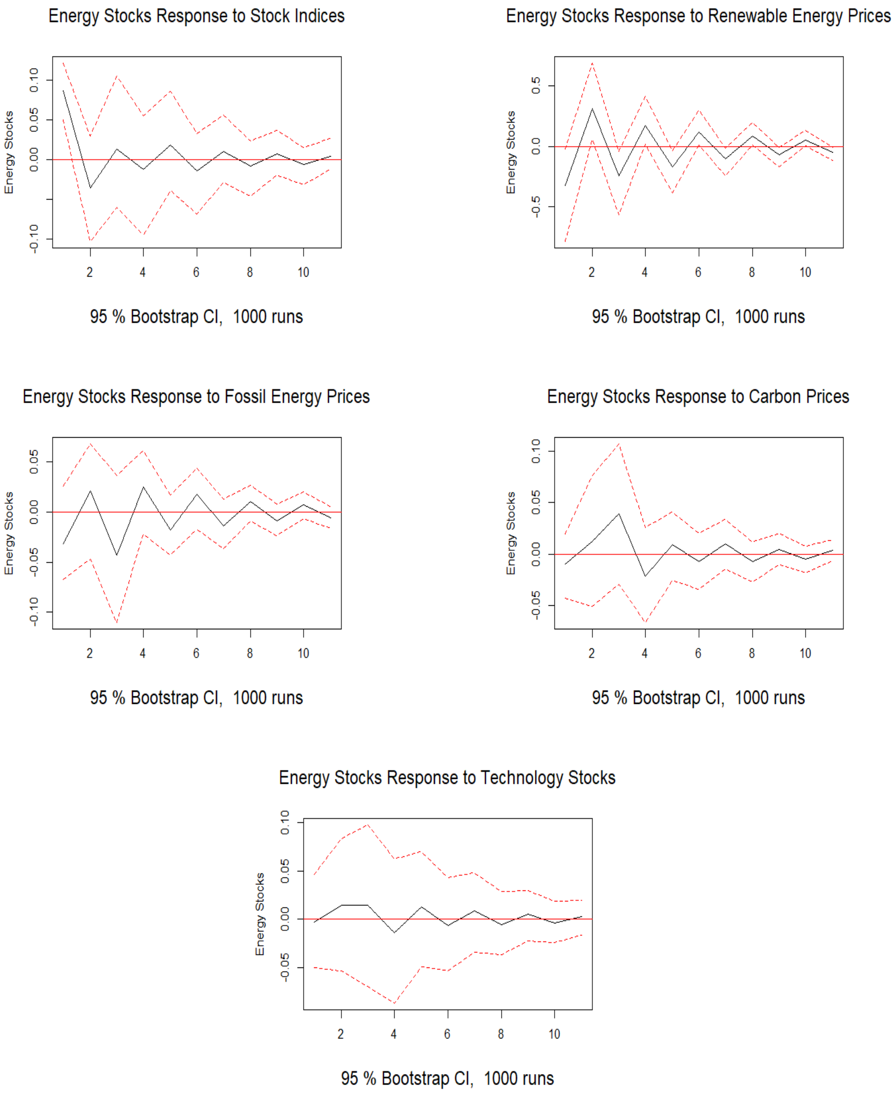

Figure 5.7: Energy Stock Prices Response

prices, that quickly fades away. The result is similar to Zhang and Du (2017) who find that the responses of energy stocks to carbon prices gradually diminish.

5.4.4 Granger Causality Test

Granger (1969)'s approach to causality does not imply a cause-effect relationship but is rather based only on the level of 'predictability' or 'forecast ability' over time. It helps detect causal, time-dependent direction between variables. We carry out Granger causality tests in Table 5.7 to identify the dynamic causal chain considering all the variables in the chain. However, these Granger causality tests can be misleading when applied to more than two variables (Brahmasrene et al., 2014). We therefore run pairwise tests in Table 5.7. In both cases, the null hypothesis is that there is no Granger causality while the alternative is that there is Granger causality. From the 'global' Granger causality tests, unidirectional causality has been detected from stock markets and energy stocks to other variables. This indicates that returns in fossil energy, renewable energy, and carbon allowances are dependent on the stock markets, as characterized by the broad and energy stock indexes.

Table 5.7: Granger Causality Test

Variables		F-stats	p-value	
RR →	FR,BSR,CR,TSR,ESR	1.5635	0.1113	No Granger Causality
FR →	RR, BSR,CR,TSR,ESR	0.48307	0.902	No Granger Causality
BSR →	RR, FR, CR, TSR, ESR	1.9202	0.03824**	Granger Causality
CR →	RR, FR, BSR, TSR, ESR	1.2989	0.225	No Granger Causality
TSR →	RR, FR, BSR, CR, ESR	0.95344	0.4825	No Granger Causality
ESR →	RR, FR, BSR, CR, TSR	7.3285	1.501e-11***	Granger Causality

***, ** and * denotes statistical significance at 1%, 5% and 10% level respectively.

In Table 5.8, unidirectional causality is only found from renewable energy to carbon prices and from energy stocks to carbon prices. Otherwise, reciprocal causality has been identified between renewable energy prices and energy stocks, stock markets and carbon prices, stock markets and technological stocks, carbon prices and technological stocks. Interestingly, fossil energy prices displays no causality from other variables nor does it Granger causes other variables. Overall, these findings confirms our previous assessment on the increasing role of renewable energy in the nexus of dynamics between energy and stocks.

Table 5.8: Pairwise Granger Causality Test

	RR	FR	BSR	CR	TSR	ESR
RR ⟶	x	0.003(0.997)	0.104(0.901)	4.541(0.011)**	0.406(0.663)	2.600(0.007)**
FR ⟶	0.0194(0.981)	x	0.672(0.511)	0.000(0.999)	1.520(0.219)	0.433(0.648)
BSR ⟶	0.405(0.667)	1.041(0.354)	x	7.512(0.000)***	5.864(0.000)***	0.989(0.373)
CR ⟶	1.177(0.308)	0.495(0.609)	2.619 (0.0734)*	x	2.997(0.051)*	1.831(0.161)
TSR ⟶	1.914(0.148)	0.679(0.507)	2.649 (0.071)*	4.061(0.017)**	x	0.877(0.416)
ESR ⟶	30.7(0.000)***	0.571(0.565)	1.012(0.364)	4.043(0.0179)**	2.11(0.122)	x

The p-values are given in parentheses. ***, ** and * denotes statistical significance at 1%, 5% and 10% level respectively.

5.4.5 Variance Decomposition

We use variance decomposition in Table 5.9 to provide information about the relative importance of the random innovations that we depicted in the previous section (Brahmasrene et al., 2014). We use Monte Carlo simulation to predict 10 observation periods. The reported numbers indicate the percentage of the forecast error in each variable that can be attributed to to innovations in each endogenous variable. It also helps assess how shocks reverberate through the nexus and how external shocks matter to each variable.

Under column (2) in the first period, 100% of the variability in renewable energy price changes is explained by its own innovations. However, it goes down over time to 87.50% after 10 periods of time. Clearly, renewable energy prices are impacted by its own shocks (of course) but then these innovations are essentially transmitted to energy intensive stock prices. After a few periods of time, these innovations in renewable energy prices explain around 10% of the forecast error

Table 5.9: Variance Decomposition (VD) Analysis

Period	VD RR	VD FR	VD BSR	VD CR	VD TSR	VD ESR
RR Shock						
1	100	0	0.00	0	0	0
2	91.22	0.002	0.003	0.192	0.162	8.421
3	89.18	0.012	0.091	0.756	0.801	9.144
4	87.87	0.012	0.155	0.907	1.045	10.10
5	87.71	0.015	0.195	0.892	1.065	10.12
6	87.84	0.015	0.191	0.918	1.053	9.982
7	87.56	0.015	0.194	0.936	1.065	10.23
8	87.53	0.016	0.201	0.942	1.078	10.23
9	87.53	0.016	0.201	0.940	1.077	10.23
10	87.50	0.016	0.201	0.940	1.077	10.26
FR Shock						
1	0.000	99.99	0	0	0	0
2	0.014	99.42	0.011	0.001	0.190	0.338
3	0.038	97.49	0.340	0.002	0.257	1.290
4	0.619	97.25	0.353	0.004	0.252	1.394
5	0.742	97.15	0.368	0.005	0.257	1.472
6	0.742	96.99	0.371	0.006	0.257	1.561
7	0.810	96.89	0.370	0.006	0.257	1.625
8	0.850	96.85	0.372	0.006	0.257	1.656
9	0.854	96.81	0.372	0.006	0.257	1.676
10	0.875	99.79	0.372	0.006	0.257	1.694
BSR Shock						
1	0.001	0.007	99.99	0	0	1.926
2	0.060	0.042	98.79	0.352	0.349	0.399
3	0.324	0.258	96.80	0.907	0.806	0.901
4	0.437	0.260	96.29	0.902	0.806	1.300
5	0.690	0.258	95.72	0.908	0.807	1.601
6	0.753	0.263	95.40	0.906	0.805	1.872
7	0.811	0.263	95.22	0.908	0.805	1.989
8	0.861	0.264	95.08	0.907	0.804	2.076
9	0.880	0.264	95.01	0.905	0.803	2.141
10	0.905	0.264	94.95	0.905	0.803	2.177
ESR Shock						
1	23.53	0.230	0	1.718	0.020	74.50
2	27.61	0.196	1.210	0.367	0.034	70.91
3	28.13	0.353	0.975	0.371	0.196	70.30
4	27.95	0.372	0.882	0.339	0.218	70.52
5	28.47	0.373	0.848	0.313	0.209	70.03
6	28.42	0.381	0.826	0.297	0.208	70.10
7	28.47	0.386	0.811	0.289	0.208	70.05
8	28.53	0.388	0.801	0.283	0.208	69.99
9	28.53	0.390	0.795	0.278	0.207	70.00
10	28.52	0.391	0.792	0.276	0.207	69.98

variance error in energy intensive stock prices.

Fossil energy prices are impacted by their own innovations. The other variables do not have significant influence on them. So fossil energy is exogenous to a certain extent in this system. The same conclusion can be drawn for the broad stock market.

This is obviously the opposite for energy intensive companies, of which innovations in their stock prices are rapidly transmitted to renewable energy prices.

5.4.6 Policy Implications

Policy design has a vital role in renewable energy development as per scientific literature (see Gatzert and Vogl (2016); Lüthi and Wüstenhagen (2012)). From the results, it can be deduced that renewable energy sources do not influence the broad companies stocks but do influence the energy companies stocks. Policy makers thus should implement regulations and frameworks to induce adoption of renewable energy amongst energy intensive companies rather than non energy intensive ones. This lack of influence of renewable energy can be due to several factors that have been indicated in literature such as; social acceptance risk (see Angelopoulos et al. (2017)) from citizens' to develop onshore wind farms given the visual disturbance and fauna at threat).

In addition, an increasing commitment to renewable energy requires additional infrastructure and resources. The considerable investment expenditure seems to be borne by energy companies rather than final consumers. Specifically, the market and regulatory risks coined as stranded assets, influence the phase out of fossil fuel and increase renewable energy. There is a need to implement stable framework to facilitate renewable energy investments. Administrative procedures as such issuance of renewable energy permits, appraisal of risks and implementation of renewable energy projects need to be improved.

Stock market coupled with energy and environmental policies is at the centre of low carbon transition of an economy. A low cost of capital is essential to encourage investments in renewable energy given the high initial costs involved. Policy makers should prioritise the development of the stock market to unlock investment in renewable energy. For example, renewable energy funds or socially responsible funds could be introduced. Given that technology can significantly impact on stock market, the policy designs should consider innovation channels to improve sustainability.

5.5 Conclusion

In the wake of international climate agreements, there have been more pledges to divest from fossil energy and transit to renewable energy. Academic studies have widely studied the time-dependent relationship between energy and stock market prices. However, they have paid attention to fossil energy prices and its impact on energy companies mainly in the US and China. Although the relationship between clean energy company stock prices and other company stock prices has been investigated, there has been no study directly dealing with renewable energy. This is in spite of the transition towards renewable energy currently under way.

In contrast to past studies which rely on clean energy stock prices as proxy for renewable energy price, our study directly rely on renewable energy tariffs and consumption to estimate the role played by renewable energy. We apply the Divisia index method to both fossil energy and renewable energy prices to provide better insights into the nexus between fossil energy, renewable energy and stock prices.

Using a sample of annual data from 2000 to 2019 for 25 countries, we provide a global perspective on the nexus between energy and stock markets. We estimate a VAR model in order to study the time-dependent dynamics between renewable energy, fossil energy, carbon emissions, and stock markets, zooming in on both energy- and technology-intensive stocks. We also analyse the related impulse response functions, Granger causality tests, and variance decompositions.

This study is the first to identify a bidirectional time-dependent relationship between renewable energy and energy-intensive stocks. When energy stock prices rise, these companies are more prosperous and more likely later to shift towards renewable energy, driving up demand and making it more valuable. Even when renewable energy prices go up, these companies tend to benefit as well, suggesting a virtuous circle. This can be explained by their greater reliance on clean energy following the disinvestment initiatives from fossil energy in the energy sector. Divestment is motivated by greater stranded asset risk, i.e., the risk of obsolescence for infrastructures built up around fossil fuels. Interestingly, renewable energy exhibits no other dynamic link with any of the outcome variables in our model, with the exception of carbon allowances. Increasing renewable energy prices motivate energy companies to increase investment in clean energy. Given that energy-intensive companies rely on emission trading systems extensively, the resulting divestment from fossil fuel leads to a decrease in demand for CO2 allowances, pushing carbon prices down.

Fossil energy displays weaker interplay than renewable energy in our study. There is no significant relationship between fossil fuel and renewable energy, carbon allowances, or stock markets, in line with several previous studies. For example, the insignificant time-dependent relationship between fossil energy and renewable energy is related to the decoupling of the two markets. Investors in conventional energy may aim to maximise their welfare at a different investment horizon than those who engage in low carbon transition projects.

Overall, our study points to renewable energy as being more a influential driver compared to fossil energy, signalling a shift in the time-dependent dynamics between stock markets and energy.

Energy-intensive company stocks are also related to technology-intensive stocks. We also find that a bullish trend in stock market prices is typically associated with booming economic activities, thereby increasing carbon emissions and ultimately raising carbon prices. Finally, greater capital injection in tech companies is deemed as a risk reduction signal, leading investors to broaden their investment base in the markets and pushing stock market index prices higher.

The impulse response functions, Granger causality tests, and variance decompositions confirm that renewable energy and energy stocks are significantly interdependent, while fossil energy seems to be rather exogenous to the nexus. In an era of international climate agreements and increasing divestment from fossil fuel, energy companies face greater regulatory risks and are increasingly sensitive to variations in renewable energy prices.

Our findings have key implications for investors and policymakers. We have assessed the dynamics of energy prices and stock markets across different countries, accounting for renewable energy which was an omitted variable in previous studies. The results sheds light on the significant role of renewable energy prices on energy stock markets, suggesting that incentives to invest in renewable energy have made a difference on its interplay with the stock markets.

The research suffers from constraints such as unbalanced representation of developed and emerging economies in the panel. There is a lack of data availability for emerging economies, thus a comparison between the two groups could not be carried out. In addition, the renewable energy prices are reported on an annual basis by OECD. We thus could not work on a higher frequency data in the study.

Several topics have emerged as possible avenues for future research. First, it would be worth using higher frequency data for renewable energy prices and stock markets to further explore their time-dependent dynamics. Likewise, the study can be replicated to account more specifically for the possible regional characteristics influencing the impact of renewable energy on stock markets.

Chapter 6

General Conclusion

The thesis provides an overview of the global interplay of carbon pricing from four different angles: dependency of carbon markets globally, the influence of news announcements, the adoption of carbon pricing mechanisms, and the presence of renewable energy as a policy along with carbon pricing. The results provide insight to policymakers and stakeholders on the governing debate on carbon pricing.

The first set of results from Chapter 2 informs us about the global dependence of carbon markets around the outcries for a single carbon price or carbon clubs. It is vital to assess the dependence structure among carbon markets, and this study extends to eight trading systems. From an economic perspective, a very low tail dependence is noted. Such traits will not leverage carbon pricing through liquidity trading or the level of pricing for inter carbon trading. While, Article 6 of the Paris Agreement (international transfer of mitigation outcomes) is being finalised, policymakers should take care of the dependence structure and devise appropriate frameworks to avoid similar pitfalls as the CDM.

Further analysis of the eight carbon markets incorporates the impact of news announcements on the prices. Chapter 3 departs from the existing studies, which were focused on market reforms or policy changes in carbon markets. Seven categories of news were matched against spot carbon prices. The results contribute to the existing literature and encourage research to go beyond the conventional factors that can impact carbon markets. The study takes into account that the carbon market operates in a dynamic environment with influences from diverse stakeholders such as lobbyists, parties to the Paris Agreement, controversies, and also policymakers. Negative news such as uncertainty or controversies, is less likely to impact carbon prices compared to positive news, such as the introduction of new carbon markets or favourable policy reforms for the environment. This helps carbon market players understand the influence of different stakeholders on prices. Eventually, it can shape and motivate a higher distribution of carbon market news via different sources. So far, Bloomberg and Carbon Pulse have dedicated platforms for carbon market news. The reach of these news stories needs to be further appraised.

The central question in Chapter 4 revolves around the race for carbon pricing mechanisms. While, there is strong advocacy to implement carbon pricing mechanisms in different forms, it is crucial to map whether the presence of several mechanisms is more efficient. Through the use of a horse race regression amongst 2,303 firms to test the relationship between carbon pricing mechanisms and environmental performance. The results inform policymakers as well as firms about the adoption of carbon pricing. It can be noted that carbon taxes implemented by governments lead to emission reductions among firms, while the other mechanisms such as carbon trading and internal carbon prices have to be adopted together to be effective. It also shows that carbon pricing is significant for carbon-intensive industries but not for other sectors. This calls for reflection on other policies and financial instruments that would reduce emissions. Firms and policymakers need to pause and assess the type of carbon pricing for different regions. The race for carbon pricing can gather many firms, but its effectiveness is questionable.

Chapter 5 contemplates the carbon pricing research at the firms' level through stock prices and by taking into account the presence of renewable energy and fossil fuel energy. It expanded across 25 countries from 2000 to 2019. The results show that carbon prices significantly influence technological stock prices. But the latter is impacted by renewable energy prices. This strengthens the rationale that carbon prices are less likely to influence stock prices on their own and in turn lead to emission reductions. However, if coupled with other policies such as decarbonization, an amplified impact on emission reductions can take place. The growing interest in using carbon pricing as a tool to combat climate change should not be isolated from other policies. Instead, there is a need to see the cross-section between other climate policies and their impact on achieving climate targets.

The primary recommendation is related to getting the carbon price right in a global environment and Article 6 of the Paris Agreement, which will allow an international transfer of mitigation outcomes. The cost of a unit of CO_2 globally will have a vital role in curbing emissions. The global climate goals can be reinforced with a carbon price floor, which will ensure the liquidity of global carbon markets. A study by IMF (2021) has investigated the introduction of an international carbon price floor that can accommodate equity considerations and emissions-equivalent alternatives to the carbon pricing. Drawing at three decades of experience from the UNFCCC, countries are unlikely to settle for a global carbon price. A potential recommendation is to go for a 'carbon pricing coalition' amongst countries/jurisdictions to enable effective climate politics. The club could apply a uniform border carbon tariff (or border carbon tax/price adjustment), with a rate no higher than the carbon price, on imports of goods and raw materials from non-members. Non-members would then feel economic pressure to join the club, and possibly even moral pressure if many countries already participate, as then non-members would be perceived as free-riders. A trade adjustment of this kind would align national interests of non-members with carbon pricing since their exports would be taxed/priced in accordance with carbon content, which could encourage them to join the coalition in order to access the carbon tax or market (e.g., permit auction) revenues and other club advantages.

There is a need to consider flexible provisions on pragmatic grounds to address equity concerns and potential obstacles to carbon pricing for some large emitters. Emerging market economies might require a lower price floor to motivate their participation due to their lower per capita income, small contribution to historical emission, and generally higher emissions intensity of production. To accelerate the development of carbon markets, policymakers might need to consider implementing complementary measures that help facilitate the environment for carbon pricing mechanisms to succeed and contribute to a significant lowering of emissions. Naturally, carbon pricing is not a silver bullet and needs to be part of a larger portfolio of climate and fiscal policies. The additional presence of non priced instruments such as regulatory regimes, outright subsidies, and other command-and-control policies may help emerging economies circumvent political economy constraints, apprehensive market failures, and inadequate green technologies.

The study has identified gaps in the global carbon pricing environment. At the firms' level, there is a lack of guidance and standards on setting an internal carbon price. There is no consensus on the rate of carbon prices that a firm should adopt, nor is there transparency on who is ultimately paying for the carbon price. Carbon pricing needs to set a long-term signal for innovation in sectors where carbon-free alternatives are not yet available. Decarbonization strategies and policies cannot be one-size-fits-all amongst firms. The results have shown the lack of incentive to decarbonize among non carbon-intensive firms who are subject to or have adopted carbon pricing.

This four-essay research study has paved the way for several future research avenues. Given the convergence of carbon clubs as per region, additional studies can be carried out while considering the market design of the carbon markets. It can appraise the similarities and differences that drive carbon prices and emissions trading. The notion of carbon leakage in a global carbon market environment, or carbon clubs, needs to be investigated. Similarly, the adoption of carbon pricing mechanisms at firm level needs to be assessed in line with their climate and other strategic policies to uncover the determinants of carbon pricing among firms. The sample and time period can also be expanded by seeking granular data from specialised climate data providers. More guidance is also needed in setting internal carbon prices and determining who bears the cost of a carbon price in place. These ideas are part of our future research agenda, which will undoubtedly try to lift the veil on carbon markets' mechanisms and how to improve them.

Appendices

Appendix A: Countries with Emission Trading Systems (ETS)

Countries	Year of Implementation	Scope
EU ETS	2005	The system covers activities from the power sector, manufacturing industry, and aviation (including flights from the EEA to the United Kingdom).
California ETS	2012	The California CaT applies to GHG emissions (CO2, CH4, N2O, SF6, HFCs, PFCs, NF3, and other fluorinated GHGs) from the industry, power, transport and buildings sectors and includes industrial process emissions.
RGGI	2009	RGGI covers CO2 emissions only from the power sector.
Quebec	2013	The Quebec CaT applies to GHG emissions from the industry, power, transport and buildings sectors and includes industrial process emissions.
China National ETS	2021	The ETS initially only applies to CO2 emissions from the power sector, including combined heat and power and captive power plants from other sectors.
South Korea ETS	2015	The ETS initially only applies to CO2 emissions from the power sector, including combined heat and power and captive power plants from other sectors.

Appendix B: Countries adopting Carbon Tax

Countries	Year of Implementation	Scope
Argentina	2018	The tax covers almost all liquid fuels and some solid products mineral coal and petroleum coke.
British Columbia	2008	The BC carbon tax applies to all fossil fuels and tires combusted for heat and energy, with some exemptions for industry, aviation, agriculture and transport users
Baja California	2020	The Baja California carbon tax applies to CO2 emissions from all sectors.The tax covers all liquid fossil fuels.
Chile	2017	The Chile carbon tax applies to CO2 emissions from mainly the power and industry sectors.The tax reform approved in 2020 modifies the threshold, establishing that as of 2023 it will apply to installations that emit 25,000 tCO2 or more, as well as to those that release more than 100 tons of particulate matter into the air each year. The tax covers all fossil fuels.
Columbia	2017	The Colombia carbon tax applies to GHG emissions from all sectors with some minor exemptions.The tax covers all liquid and gaseous fossil fuels used for combustion.
Denmark	1992	The Denmark carbon tax applies to GHG emissions from mainly the buildings and transport sectors as there are (partial) exemptions for other sectors.
Estonia	2000	The Estonia carbon tax applies to CO2 emissions from industry and power sectors.The tax covers all fossil fuels used to generate thermal energy.
Finland	1990	The Finland carbon tax applies to CO2 emissions from mainly the industry, transport and buildings sectors with some exemptions for industry. The tax covers all fossil fuels except for peat.
France	2014	The French carbon tax applies CO2 emissions from mainly the industry, buildings and transport sectors with some exemptions for these and other sectors.
Iceland	2010	The Iceland carbon tax applies to CO2 emissions from all sectors with some exemptions for the industry, power, aviation and international shipping sectors
Ireland	2010	The Ireland carbon tax applies to CO2 emissions from all sectors with some exemptions for the power, industry, transport and aviation sectors.
Japan	2012	The Japan carbon tax applies to CO2 emissions from the combustion of fossil fuels across all sectors with some exemptions for the industry, power, agriculture and transport sectors.
Latvia	2004	The Latvia carbon tax applies to CO2 emissions from the industry and power sectors not covered under the EU ETS.
Luxembourg	2021	Luxembourg carbon tax applies to fossil fuels used for transportation and heating. Fossil fuels used for electricity generation are exempt from the carbon tax.
Mexico	2014	The Mexican carbon tax applies to CO2 emissions from all sectors.
Netherlands	2021	The Netherlands carbon tax applies to emissions from industry and waste sectors.
Norway	1991	The Norwegian taxes on emissions of GHGs applies to GHG emissions from all sectors with some exemptions for certain sectors.

Poland	1990	The Poland carbon tax applies to GHG emissions from all sectors with some exemptions for certain entities.
Portugal	2015	The Portugal carbon tax applies to CO2 emissions from mainly the industry, buildings and transport sectors with some exemptions for these and other sectors.
Singapore	2019	The Singapore carbon tax applies to direct emissions from facilities emitting 25 ktCO2e or more in a year, covering carbon dioxide, methane, nitrous oxide, sulphur hexafluoride, hydrofluorocarbons, and perfluorocarbons. The carbon tax is applied on all sectors without exemption as long as the facility meets the emissions threshold.
Slovenia	1996	The Slovenia carbon tax applies to GHG emissions from mainly the buildings and transport sector as there are exemptions for other sectors.
South Africa	2019	The Carbon Tax covers all types of fossil fuels combusted by large businesses across industry, power, and transport sectors.
Spain	2014	The Spanish carbon tax applies to fluorinated GHG emissions (HFCs, PFCs, and SF6) only from all sectors with some exemptions for certain sectors.
Sweden	1991	The Swedish carbon tax applies to CO2 emissions from mainly the transport and buildings sector as there are many (partial) exemptions for other sectors.
Switzerland	2008	The Swiss CO2 levy applies to CO2 emissions generated from fossil heating and process fuels when used in the industry, power and buildings sectors.
Ukraine	2011	The Ukraine carbon tax applies to CO2 emissions from stationary sources, so mainly the industry, power and buildings sectors and all types of fuels.

Appendix C: List of countries and their stock indices

Countries	Broad Stock Index	Technology Index	Energy Index
Australia	S&P 200	S&P Tech	MSCI Energy
Austria	Austrian Traded Index	MSCI Austria IMI Information Technology Sector Price Index	MSCI Austria Energy Sector Price Index
Canada	Toronto 300	S&P Canadian IT index	S&P/TSX Energy and Clean Tech
China	Shenzhen CSI 300	MSCI International China Tech Index	MSCI International China Energy Index
Czech Republic	PX Prague SE Index	STOXX Europe Technology	EEX EEX Index
Denmark	MSCI Denmark	OMX Copahengen Technology	Nasdaq Denmark Energy Index
Estonia	OMX Tallinn	OMX Baltic Technology Index	MSCI Europe Energy Index
France	CAC440	CAC Tech Index	CAC Energy Index
Germany	DAX	TecDax	Dax Subsector all renewable energy
Greece	Athex Composite Share Price Index	FTSE/Athex Technology Index	AT FTSE Energy Index
India	Nifty Tri Index	MSCI India Tech	Refinitiv India Energy Index
Indonesia	Jakarta SE Composite Index	Indonesia SE Technology Index	Refinitiv Indonesia Energy Index
Italy	FTSE MIB Index	MSCI Italy IMI Information Technology Sector Price Index	FTSE ITALIA ALL-SHARE ENERGY Price Return Index

Countries	Broad Stock Index	Technology Index	Energy Index
Japan	Nikkei	CNINFO 1000	Refinitiv Japan Energy Index
Korea	Korea SE Kospi 200 Index	MSCI Korea IT Sector	Refinitiv Korea Energy Index
Luxembourg	Luxembourg SE LuxX Index	STOXX Europe Technology	MSCI Europe Energy Index
Netherlands	Refinitiv Netherlands Index	AEX Technology Index	AEX Energy Index
Portugal	Euronext Lisbon PSI 20 Index	PSI Technology Gross Return Index	MSCI Portugal Energy Sector Price Index
Slovakia	SAX Index	STOXX Europe Technology	MSCI Europe Energy Index
South Africa	FTSE/JSE Top 40 companies	FTSE/JSE Tech Index	MSCI International South Africa Energy Sector Index
Spain	Madrid General SE Index	MSCI International Spain Information Technology Price Index	Madrid SE Energy Index
Switzerland	Swiss Market Index	MSCI Switzerland IMI Information Technology Sector Price Index	MSCI International Switzerland Energy industry group Investable Price Index
Turkey	BIST 100 Index	BIST Tech Index	FTSE Energy Index
UK	FTSE	FTSE Tech	MSCI Energy UK
USA	S&P500	Nasdaq 100	Clean Energy Index

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