Carbon Pricing, Renewable Energy, and Clean Growth
A Market Perspective

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Carbon Pricing, Renewable Energy, and Clean Growth

– A Market Perspective

Chenyan Lyu

A Thesis presented for the degree of Doctor of Philosophy

Primary Supervisor: Tooraj Jamasb

Secondary Supervisor: Lisbeth La Cour

CBS PhD School

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Preface

This PhD thesis represents the culmination of my childhood dream. I grew up in a place surrounded by forests, and I have always been fascinated by the beauty and harmony of the ecosystem and dreamed that one day I could contribute wisely to it. Heavy haze pollution enshrouded Beijing in 2013 when I had just started my Bachelor's degree in Agriculture and Forestry. I started thinking of where the pollution came from while wearing my N95 mask in 2013. The answer was the burning of fossil fuels which results in smog. Coal burning is causing severe health problems for our generation, and ignorance of negative environmental externalities leads to difficulties in implementing environmental policy reform. Thus, I decided to go for advanced finance and economics studies to better understand environmental problems from a macro-level and would like to contribute to energy and environmental policymaking. Many people around the world have inspired me in different ways along this path, enriching my life in many ways I could never have imagined. First of all, thanks to my parents, who supported me in pursuing the MSc and Doctoral training in Europe and encouraged me during the challenging COVID-19 period.

My PhD journey started in Durham University, UK in 2019. I would like to express my sincere gratitude to my primary supervisor Professor Tooraj Jamasb for the academic support and participating in my journey, from UK to DK. And thanks to my secondary supervisor, Professor Lisbeth La Cour, who has worked tirelessly with editing and reviewing process of my first paper.

Professor Bert Scholtens has been my first, and most significant co-author. Bert has kindly invited me for a research visit at the University of Groningen, where I met good

friends and had a fruitful time later. I enjoyed every lunch break walk in Groningen and the tour to Winsum. I can barely express my gratitude to Bert, but I have no doubt that more groundbreaking ideas and creative papers will emerge from our joint efforts.

Thanks to my committee member, Professor Anne Neumann, Professor Bing Xu, Professor Ismir Mulalic, and Professor Ugur Soytas.

Thanks to Professor Brian Wu, being an inspiring mentor who shed light on my education path. A profound sense of gratitude binds me to a group of my friends, Professor Jean Michel Glachant, Lina Xie, Oguzhan Cepni, Yehan Wu, Yue Zhao.

My most profound appreciation goes out to Dr. Myriam Marending and Dr. Stefano Tripodi, who have been my most incredible colleagues and life friends. A special thank you goes out to Lyz Liu for supporting me during the challenging PhD journey. They are friends and family who constantly give me a lot of energy when it's gloomy in the winter in Scandinavia.

The new chapter has just started.

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Abstract

This PhD thesis explores the carbon market integration and risk sharing mechanism across markets, from developing carbon pilot markets in China, to global leading carbon markets in EU, US, and New Zealand. The last chapter of the thesis explores spillovers across highly geographically integrated Nordic electricity markets, as well as the impact of carbon price shocks on the volatility spillovers in Nordic electricity markets.

In the first chapter "Dynamics of regional carbon markets in China", I look at the dynamic linkages across China's nine ETS systems. Since launch, China's regional and national Emission Trading Schemes are fast-growing, forming the largest ETS systems in the world. China's growing carbon markets are still relatively weak in terms of legal foundation, market regulation development, and price maturity. These differences have led to the existence of ten carbon prices in one country which induce difficulties to unify the cost of emission reduction in China. The purpose of the paper is to test the hypothesis of the existence of a single carbon price for China's pilot Emission Trading Schemes. By testing, this paper seeks to advance our understanding of the efficiency of China's carbon spot prices by looking at the spatial properties of eight regional ETS and one national ETS. Empirically, the cointegration and vector error correction model are applied to examine the carbon market integration level in China, from 2014 to 2022. The insight into economic and energy structure in the different regions where carbon markets operate is important for improving the richness of the carbon market architecture analysis. The results are highly relevant for investors and policy makers worldwide.

In the second chapter "Is the Global Carbon Market Integrated? Return and Volatility Connectedness in ETS Systems", we measure the return and volatility spillovers across four international carbon markets. The Emission Trading Scheme is gaining momentum with its increasing market size and constantly improving information mechanisms. With carbon assets becoming prominent as an alternative asset class, the ETS market has engaged a broad

range of participants, including not only emissions-intensive energy corporations but also individual and institutional investors. This paper examines how market fluctuations in these carbon markets interact with each other across four jurisdictions – European Union, New Zealand, California, and Hubei (China). We study return and volatility data, covering the period April 2014 - December 2021, relying on the Time-Varying Parameters Vector Autoregressive model to appreciate the markets' connectedness. We find that the dynamics of carbon markets is mainly explained by itself. Global negotiations and carbon market events have only a minor impact on the level of connectedness, in contrast to energy or financial crises and the Covid-19 outbreak. We also establish that market size is an important shock absorber.

The third chapter "Volatility Spillovers in the Interconnected NordPool Electricity Markets – The Effect of Carbon Price" analyses the electricity market integration and the impacts of carbon price in NordPool markets. Integration of electricity markets remains a cornerstone of the European economic integration. However, the price of electricity in liberalized wholesale electricity markets has become one of the most volatile financial instruments with its dependence on weather and climate-related conditions, the growing share of renewables, and the increasing marginal cost of carbon that the electricity generators are facing. The European Union emissions trading system (EU ETS), as a well-established carbon market in the EU, will increase electricity price levels in general. We use the connectedness approach based on both the time-varying parameter VAR (TVP-VAR, thereafter) and rolling window-based VAR (RW-VAR, thereafter) models to analyse integration in Nordic electricity markets, contributing to the scare literature in the electricity volatility connectedness across four countries (Sweden, Finland, Denmark, Norway). Then, we examine how changes in carbon price influence those spillover effects. Understanding these issues is important for market participants to adopt appropriate risk management strategies to reduce the negative effects of electricity price volatility. It is also important for the regulators of electricity markets to devise appropriate policies to address potential electricity crises and to maintain electricity market stability. Our results show that Sweden is a net volatility spillover transmitter while Denmark bears the most significant shocks from the system.

Abstrakt

Denne ph.d.-afhandling undersøger integrationen af CO2-markedet og risikodelingsmekanismen på tværs af markederne, fra udvikling af CO2-pilotmarkeder i Kina til globale førende CO2-markeder i EU, USA og New Zealand. I afhandlingens sidste kapitel undersøges afsmittende virkninger på tværs af stærkt geografisk integrerede nordiske elmarkeder samt virkningen af kulstofprischok på volatilitetsafsmittende virkninger på de nordiske elmarkeder.

I det første kapitel "Dynamics of regional carbon markets in China" ser jeg på de dynamiske forbindelser på tværs af Kinas ni ETS-systemer. Siden lanceringen er Kinas regionale og nationale emissionshandelsordninger vokset hurtigt og udgør de største ETS-systemer i verden. Kinas voksende CO2-markeder er stadig relativt svage med hensyn til retsgrundlag, udvikling af markedsregulering og prismodning. Disse forskelle har ført til, at der findes ti kulstofpriser i ét land, hvilket gør det vanskeligt at ensrette omkostningerne ved emissionsreduktion i Kina. Formålet med denne artikel er at teste hypotesen om eksistensen af en enkelt CO2-pris for Kinas pilotordninger for handel med emissioner. Ved at teste denne artikel søger vi at fremme vores forståelse af effektiviteten af Kinas spotpriser på kulstofområdet ved at se på de rumlige egenskaber ved otte regionale emissionshandelsordninger og én national emissionshandelsordning. Empirisk anvendes kointegrations- og vektorfejlkorrektionsmodellen til at undersøge integrationsniveauet på CO2-markedet i Kina fra 2014 til 2022. Indsigten i den økonomiske og energimæssige struktur i de forskellige regioner, hvor CO2-markederne opererer, er vigtig for at forbedre analysen af CO2-markedsarkitekturen. Resultaterne er yderst relevante for investorer og politiske beslutningstagere i hele verden.

I det andet kapitel "Is the Global Carbon Market Integrated? Return and Volatility Connectedness in ETS Systems" måler vi afkast- og volatilitetsspilloverne på tværs af fire internationale CO2-markeder. Emissionshandelsordningen er ved at få fart på med sin

stigende markedsstørrelse og konstant forbedrede informationsmekanismer. Da kulstofaktiver er blevet fremtrædende som en alternativ aktivklasse, har ETS-markedet engageret en bred vifte af deltagere, herunder ikke kun emissionsintensive energiselskaber, men også individuelle og institutionelle investorer. I denne artikel undersøges det, hvordan markedsudsving på disse CO2-markeder interagerer med hinanden på tværs af fire jurisdiktioner - Den Europæiske Union, New Zealand, Californien og Hubei (Kina). Vi undersøger afkast- og volatilitetsdata, der dækker perioden april 2014 - december 2021, og benytter os af den tidsvarierende parametre-vektorautoregressive model til at vurdere markedernes indbyrdes sammenhæng. Vi finder, at dynamikken på CO2-markederne hovedsagelig forklares af sig selv. Globale forhandlinger og begivenheder på CO2-markedet har kun en mindre indvirkning på graden af forbundethed i modsætning til energi- eller finanskriser og Covid-19-udbruddet. Vi fastslår også, at markedsstørrelse er en vigtig støddæmper.

I det tredje kapitel "Volatility Spillovers in the Interconnected NordPool Electricity Markets – The Effect of Carbon Price" analyseres integrationen af elmarkederne og virkningerne af kulstofprisen på NordPool-markederne. Integrationen af elmarkederne er fortsat en hjørnesten i den europæiske økonomiske integration. Prisen på elektricitet på liberaliserede engrosmarkeder for elektricitet er imidlertid blevet et af de mest ustabile finansielle instrumenter med sin afhængighed af vejr- og klimarelaterede forhold, den stigende andel af vedvarende energikilder og de stigende marginale kulstofomkostninger, som elproducenterne står over for. Den Europæiske Unions emissionshandelsordning (EU ETS), som er et veletableret CO2-marked i EU, vil generelt øge elprisniveauet. Vi anvender en tilgang til sammenhængen baseret på både tidsvarierende parameter-VAR-modeller (TVP-VAR, herefter) og rullende vinduesbaserede VAR-modeller (RW-VAR, herefter) til at analysere integrationen på de nordiske elmarkeder og bidrager dermed til den sparsomme litteratur om sammenhængen i elvolatiliteten på tværs af fire lande (Sverige, Finland, Danmark og Norge). Derefter undersøger vi, hvordan ændringer i kulstofprisen påvirker disse afsmittende virkninger. Det er vigtigt at forstå disse spørgsmål for markedsdeltagerne, så de kan vedtage passende risikostyringsstrategier for at reducere de negative virkninger af volatiliteten i elpriserne. Det er også vigtigt for reguleringsmyndighederne på elmarkederne at udforme passende politikker til at håndtere potentielle elkriser og opretholde stabiliteten på elmarkedet. Vores resultater viser, at Sverige er en nettosender af volatilitetsspillover, mens Danmark bærer de mest betydelige chok fra systemet.

Introduction

Carbon pricing is a policy tool that encourages the transition towards a decarbonized economy. This approach creates a financial incentive to reduce emissions through economic price signals. Emitters can choose to either reduce their emissions by adopting cleaner technologies or paying for the carbon cost. Therefore, by incorporating the cost of climate change into economic decision-making, carbon pricing can stimulate new, low-carbon drivers of economic growth, and the overall environmental goal is met in the most flexible and cost-effective way to society. A carbon price can be implemented as a tax or as an Emissions Trading System (ETS). Empirical research suggest that carbon pricing is an effective policy, as it helps to promote clean technology, and thus, leading to a change in production and consumption patterns. Theoretically, both ETS and carbon tax will eventually lead to equal marginal abatement costs for polluters (Stavins, 1997).

ETS follows the Coase Theorem (Kahneman et al., 1990), which posits that while the environment is a public good, emissions of greenhouse gases (GHG) pose a negative externality. Typically, the ETS operates on a 'cap and trade' principle, which sets a limit for the total allowable emissions for each regulated entities in a given area at the start of each compliance year. The initial emission allowances are either auctioned or freely allocated to the regulated entities. By creating the supply and demand for emission permits, an ETS sets a market price for GHG emissions. ETS is flexible, simplifies the government's work, and reduces the regulatory cost (Dales, 1968; Montgomery, 1972). Importantly, the ETS has advantage in addressing heterogeneity in marginal abatement costs. The Kyoto Protocol designed three carbon emission-trading mechanisms: International Emission Trade (IET), Joint Implement (JI), and Clean Development Mechanism (CDM). At present, over 46 countries and more than 28 cities, states and provinces use carbon-pricing mechanisms including Quebec, China, Beijing, Shanghai, Chongqing, Tianjin, Guangdong, Shenzhen, Hubei, EU ETS, and Tokyo. Regions such as Chile, Thailand, Turkey, Vietnam, Oregon, and Washington are also considering developing carbon markets. This thesis contributes to the literature of carbon market integration and the impact of carbon price on power markets.

Cassel (1918) is considered to be one of the earliest references introducing the concepts of purchasing power parity and the law of one price (LOP). In more recent times, Stigler (1969) conceived of a market as "the area within which the price of a commodity tends to uniformity, allowing for the transportation costs". The application of cointegration methods to the analysis of spatial price relationships has then become common, both to test the LOP and to understand the degree to which different regions/markets are integrated (Goodwin, 1992; McNew and Fackler, 1997).

The first chapter chooses co-integration and vector error correction model to study the relationship between prices across nine ETS markets, a method that has been used for many years to do research on market integrations and has been successful. Albeit researchers have argued that the 'cointegration does not imply integration', the relationship between the economics concepts of the LOP and market integration and the statistical concept of cointegration is a complex one. There is a substantial empirical literature concentrated mainly on cointegration and vector error correction model to examine price relationships as a way to investigate market integration. I find that five major regional ETS in China are cointegration at rank one, between 2014 and 2019. The analysis for nine ETS from July 2021 to July 2022 is examined to have rank three cointegrating relationship, which means the markets are more integrated than the period of 2014-2019. This more favorable result could be attributable to the analysis's use of the most recent data sample (2021-2022) and the inclusion of a more ETS markets. However, the national ETS has not yet enter the long run cointegrating relationships with other regional ETS after a year operation.

In the recent ten years, the network connectedness approach is popular in market integration research. Diebold and Yilmaz (2009, 2012) establish a connectedness framework for analysing both idiosyncratic and extrinsic effects based on the estimation of the forecast error variance decompositions (FEVD) from a Vector autoregression model (VAR). This approach has been applied to spillovers in electricity markets (Do et al., 2020; Han et al., 2020; Ma et al., 2022), crude oil markets (Liu and Gong, 2020), gas market volatility (Broadstock et al., 2020), and energy company stock returns and volatility (Geng et al., 2021a, 2021b; Wu et al., 2021).

The second chapter elaborates on this trend of literature as the aim is to provide a more flexible framework to analyze the time-variation in carbon markets. This is the first study to employ the Time Varying Parameter VAR (TVP – VAR) model with the connectedness approach introduced by Diebold and Yilmaz (2012, 2009). This approach helps identify aggregated and directional return and volatility connectedness, which differentiate which ETS markets are net transmitters, and which are net receivers. The approach identifies the main risk triggers of each ETS in the system, and links to specific market microstructure and mechanism. We find that the dynamic connectedness of return and volatility networks changes considerably over time, especially during Covid-19 outbreak. This suggests that spillover across carbon markets is a time-dependent phenomenon. We establish that the average return (volatility) total connectedness index (TCI) is 10.42% (12.10%), which indicates that the global carbon prices are largely dependent. Changes in global climate change politics and carbon market reforms appear to have only minor impact on TCI, whereas the occurrence of energy and financial crises have a substantial effect (both regarding return and volatility). The EU ETS has a persistent net-transmitting role, as it is the largest and only transmitter in return connectedness, whereas the California's cap and trade (CA CaT) is the largest transmitter in the volatility connectedness. New Zealand's ETS is the largest shock receiver in both the return and volatility connectedness systems.

The power sector is the first regulated sector in the EU ETS and is always the sector with the highest CO2 emissions and is the most significant carbon trading participant. Higher carbon prices encourage investment in clean power generation and less carbon-intensive technologies, whereas lower carbon prices revive the attractiveness of fossil fuel power generation. The Nordic electricity market - NordPool is believed to be the most well-functioning market in the world (Amundsen and Bergman, 2006). The third chapter analyses volatility spillovers across the four Nordic countries and examine how carbon prices influence those spillover effects. The research questions which this study is trying to answer include: what is the volatility connectedness level among the Nordic countries? Whether and how changes in carbon prices drive volatility spillovers in integrated Nordic electricity markets?

Chapter 1

Dynamics of regional carbon markets in China

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1. Dynamics of regional carbon markets in China

Summary
Since launch, China's regional and national Emission Trading Schemes are fast-growing, forming the largest ETS systems in the world. China's growing carbon markets are still relatively weak in terms of legal foundation, market regulation development, and price maturity. These differences have led to the existence of ten carbon prices in one country which induce difficulties to unify the cost of emission reduction in China. Notably, disjoint regional markets have caused market inefficiency, increasing the difficulty of reflecting the true value of carbon emission cost in the jurisdiction. The purpose of the paper is to test the hypothesis of the existence of a single carbon price for China's pilot Emission Trading Schemes. By testing, this paper seeks to advance our understanding of the efficiency of China's carbon spot prices by looking at the spatial properties of eight regional ETS and one national ETS. Empirically, the cointegration and vector error correction model are applied to examine the carbon market integration level in China, from 2014 to 2022. The insight into economic and energy structure in the different regions where carbon markets operate is important for improving the richness of the carbon market architecture analysis. The results are highly relevant for investors and policy makers worldwide.

1.1 Introduction

China accounts for the largest share, which represents 28% of the world's total greenhouse gas emission (International Energy Agency, 2022). The scale and growth of industrial activities and energy consumption in China explain the high level of emissions. In September 2020, China announced ambitious goals for sustainable energy and carbon neutrality by 2060, and to curb peak carbon emissions by 2030 (People's Republic of China, 2016). With increasingly stringent energy-saving goals, green technologies, ongoing climate mitigation and adaptation, China aims to reduce carbon emissions by about 70% from the current level by 2050 (Energy Foundation China, 2020). In the past, China has mostly relied on administrative tools to reduce carbon emissions. Achieving "carbon neutrality" through administrative means can be effective but also costly and inefficient. The National Development and Reform Commission of China was aware of this dilemma, and this was reflected in the plan to launch the regional and national emission trading schemes for 2013 and 2021 respectively (People's Republic of China, 2020). Since launch, the nine[1] regional and one nationwide Emission Trading Schemes (ETS) are fast-growing, which cover in total 5426 million tons of CO2 emissions in China, forming the largest ETS systems in the world (Stoerk et al. 2019). Albeit the combined size of these markets is larger than world's leading carbon market, the European Union Emission Trading Scheme (EU ETS), China's carbon market is still relatively weak in terms of legal foundation, market regulation development, and price maturity. The pilot areas cover a range of different economic circumstances. The pilot markets vary greatly not only in the aspects of sector coverage and market regulation, but also the selection of regulated industries, the degree of openness to investors, and the construction of the legal system (World Bank, 2021). These differences have led to the existence of ten carbon prices in one country which induce difficulties to unify the cost of emission reduction in China. In this threshold, this paper considers these pilots as cross-regional independent markets. Moreover, the remaining provinces and special zones in China have not introduced carbon prices yet, greatly enhances the risk of carbon leakage within the country[2].

Along-term goal for developing Emission Trading Schemes at the regional level is to create a single integrated market with comparable pricing across provinces in China (Hua and Dong, 2019). Several reasons have been postulated for the growing interest in regional ETS integration: the regional ETS are regulated directly by local governments, but both indirectly influenced by carbon reduction policies issued by central government; the increased flow of

[1] Nine pilot ETS includes Beijing ETS (citywide), Shanghai ETS(citywide), Shenzhen ETS(citywide), Chongqing ETS (citywide), Tianjin ETS (citywide), Guangdong ETS (provincial), Hubei ETS (provincial), Fujian ETS (provincial), and Sichuan ETS (provincial).

[2] Although the national ETS in China is open to all provinces across the country, it is currently only for power sector, there are many other high emitting industries still facing zero carbon cost.

capital across provincial boundaries due to the relaxation of controls on non-institutional participants and investors; improvements in the flow of information; and the potential gains from diversification of investments on both domestic and international levels. Arbitrage activity should maintain the prices of perfect substitutes trading on separate markets tightly linked (Mizrach, 2012a). Notably, disjoint regional markets have caused market inefficiency, increasing the difficulty of reflecting the true value of carbon emission cost in China.

The purpose of the paper is to test the hypothesis of the existence of a single carbon price for China's pilot Emission Trading Schemes (ETS). By testing, this paper seeks to advance our understanding of the efficiency of China's carbon spot prices by looking at the spatial properties of eight regional[3] ETS and one national ETS. Empirically, the paper tests the relationship of five major regional market monthly prices from 2014 to 2019; and then tests the dynamics of nine ETS with the use of daily prices from Jul 2021 to Jul 2022, the integration level of China's carbon price is examined. China is a large, populous, and diverse country and the performance of its carbon markets has regional, national, and global effects. Therefore, it would be of some importance to analyse the dynamic fluctuations (in terms of lead-lag relationships) of the emerging ETS in China.

The contribution of this paper is threefold. First, this paper pays attention to the interactions among China's regional ETS and national ETS. To the best of my knowledge, this is the first study investigates the relationship between carbon prices of nine ETS – Beijing, Chongqing, Fujian, Guangdong, Hubei, Shanghai, Shenzhen, Tianjin, and national ETS in China. Secondly, this paper employs the co-integration technique and vector error correction model (VECM). The overall results add important empirical evidence, enriching the carbon market integration literature with more emerging ETS markets. The study aims to clarify to what extent the objective of creating and single national carbon markets has been achieved. Third, the insight into economic and energy structure in the different regions with carbon trading of China is important for improving the richness of the carbon market architecture analysis.

[3] This paper excludes Sichuan regional ETS due to the shortest time span, and lack of data, which is consistent to the view of (Guo and Feng, 2021).

As China's ETS are developing into the world's largest, more foreign institutional and individual investor would engage in carbon trading in China. Understanding the market architecture, as well as which market is leading the others in short- or long- term can help investor make better portfolio diversification decisions. The results are highly relevant for investors and policy makers worldwide.

The remainder of the paper is organized as follows: Section 2 reviews the relevant literature on emission trading schemes globally and domestically. Section 3 presents the market architecture in China's regional carbon markets, allocation methods, and regulation. Section 4 presents the methodology and models to estimate the spillover effects among different regional ETSs in China. Section 5 describes the data used in this study. Section 6 discusses the empirical results. Section 7 is conclusions with policy implications.

1.2 Background

1.2.1 Market architecture of China's ETS pilots

There are differences in natural resources and climatic features among nine markets in this study, as well as significant differences in economic development, energy market structure, and residents' willingness to offset carbon emissions. Beijing, Shanghai, Shenzhen, and Guangzhou are the four most economically powerful cities in China and in the forefront of China in terms of GDP growth. The increase in energy intensity associated with economic expansion has also increased carbon emission intensity. These four cities, each with its unique characteristics, are actively exploring the carbon markets. Hubei Province is relatively less developed but is representative of the national average, with an economic structure dominated by heavy industry (Jotzo and Löschel, 2014). Chongqing, Tianjin, Fujian ETS are relative smaller in market size. The national ETS just started trading since July 2021, and it only regulates power sector initially. The current allowance allocation in Chinese regional and national ETSs highly relies on grandfathering and benchmarking, similar to phases 1 and 2 (2005-2012) in the EU ETS. Even though China's pilots attempted an auction mechanism to allocate the allowances, the primary objective appears to be to reduce the price to attract more participants, with social welfare having a lower priority. In terms of a carbon secondary market, the price of emission allowances was volatile around the compliance deadlines, which signals a cyclical behavior across all the Chinese ETS pilots. The cyclical price behavior in carbon trading has mainly reflected the ETS compliance function. The motivation of regulated units to spontaneously reduce carbon emissions is relatively weak. Table 1 summarizes the main differences among regional ETS pilots.

Beijing ETS

Beijing is the center of the country's economy, culture, and foreign relations. Its urban strategic positioning necessitates vigorously promoting ecological construction and improving environmental quality. Beijing ETS was designed at the top level, taking the lead in defining the legal framework and effectiveness of a carbon trading system at the local level (Beijing Municipal Commission of Development and Reform, 2013). Beijing's carbon trading products are diverse and include not only local allowances and carbon offset products but also forestry carbon sink projects and energy-saving emission reductions. Given the concern that over 65% of total electricity consumption in Beijing is imported from other provinces, indirect emissions from electricity generation both within and outside the Beijing are covered in Beijing ETS (Feng et al., 2013). Since 2014, the Beijing ETS has pioneered cross-regional carbon emissions trading, and prioritizes cross-regional trading with Hebei Province and Inner Mongolia Autonomous Region. Beijing and Shenzhen are the only ETS pilots regulated by their municipal legislators, which provides higher legal regulation stability. In comparison to other regional ETSs, Beijing ETS has a relatively high carbon price and a relatively small trending change, which is conducive to encouraging businesses to contribute to energy conservation and emission reduction.

Shanghai ETS

Located in the Yangtze River Delta, Shanghai is the country's most vibrant commercial and financial hub (Development Research Center of the State Council and World Bank, 2013). It has progressed in green economic growth, technological industry development, and carbon market development. The energy production of the city still includes coal, but in a far smaller proportion than at the national level. Shanghai took the lead in building pilot carbon trading in 2011 and officially launched the Shanghai ETS in November 2013. At its inception, Shanghai ETS established the most detailed and thorough report and regulation guidance of all China's ETS pilots (Shanghai Municipal Bureau of Ecology and Environment, 2021). However, the legal foundation of Shanghai ETS is relatively weak and incomplete. With the launch, the Shanghai ETS is the only pilot in China to have achieved 100% compliance for continuously seven years. It has now covered 57% of the city's emissions. Building a complete measurement, reporting, and verification and legal framework tailored to its region would be the next challenge for Shanghai ETS. In 2021, the trading platform for the national ETS was launched in Shanghai.

Guangdong ETS

Guangdong province hosts major port facilities on the South China Sea and is a prominent channel for both domestic and international transportation and trade. Its annual global trade volume accounts for nearly a quarter of China's total. Connected to its active and wide-ranging economy, the Guangdong ETS has a high level of freedom and openness. It was the first pilot[4] opened to foreign investors and it allows unincorporated organizations, such as funds and trusts, to trade in its markets. The Guangdong ETS has become China's largest carbon trading center with the largest market share and increasing liquidity. It is currently trading over 60% of the province's emissions (ICAP, 2020). Guangdong ETS has gradually established a multi-level market system in which the primary and secondary markets interact with each other. At present, Guangdong ETS has successfully organized 16 allowances auctions, with an auction revenue of about 800 million yuan, which signals an occurrence of a mature carbon market. Its auction design is exceptional among all pilots. In addition, the Guangdong ETS is close to completing third-party verification regulations.

Shenzhen ETS

Shenzhen ETS pilot has legislative authority over its own territory, and was the earliest ETS pilot running in China, in 2013. The main regulated target of Shenzhen ETS is corporate

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[4] Guangdong ETS and Shenzhen ETS now are both open to foreign investors. Shenzhen is a major city in Guangdong province. Shenzhen ETS and Guangdong ETS operate in parallel.

organizations rather than facilities. The government has designed dual emission reduction targets — an absolute cap target for whole regulated industries, and relative emission reduction targets for each of the control units (Shenzhen Municipal Bureau of Ecology and Environment, 2021). The total absolute emission cap can be increased year by year, but the carbon intensity for each participant, and the overall average carbon intensity target, need to be decreased over time. To encourage enterprises in tertiary industry to participate in carbon trading, the initial inclusion threshold for Shenzhen ETS is quite low at 3000 $tonCO_2/year$, even lower than Beijing's (5,000).

Hubei ETS

The economic growth rate, the share of primary, secondary and tertiary industries, and the overall energy structure of Hubei Province are reflective of China as a whole country (Qi et al., 2014). In comparison to the other four pilots, Hubei is more representative of a wide range of provinces in China, being strongly reliant on secondary industries and coal consumption, while the inflexible demand for energy consumption continues to develop at an exponential rate. The Hubei ETS pilot prioritizes stability above development. It is provincial in scope, encompassing numerous administrative levels ranging from urban to rural. The Hubei ETS, begun in 2014, quickly became one of the most active ETS pilots, with the highest traded volume and turnover rates among all regional pilots over its first two compliance years. Hubei ETS went on to increase its scope of regulated sectors in subsequent years, including the ceramics, food, and beverage industries (People's Government of Hubei Province, 2014). In the beginning, the entry requirement for Hubei ETS was that each participant must emit at least 60,000 tons of CO2 per year. That threshold has been lowered to 10,000 tons. Hubei ETS has a great diversity of market participants, including energy companies, institutions, and individual investors. In 2020, Hubei ETS took on the mission of establishing the registration system for national ETS.

Chongqing, Tianjin, and Fujian

Chongqing launched its citywide pilot ETS in June 2014, with 152 enterprises covered while accounting for around 51% of the city's total emission in 2020 (ICAP, 2021). It is the only

ETS in China that covers all six greenhouse gases specified in the Kyoto Protocol (Li et al., 2022). Tianjin is also a citywide ETS that starter in December 2013, it is slowly developing by construction legal foundation and introduce auctions. Guo and Feng (2021) reports that Chongqing ETS price is highly volatile while Tianjin ETS shows the opposite. Fujian ETS, as provincial ETS, started in September 2016. Fujian ETS is unique in its cover of natural forest which extending over 64% of its land area. Hence, its ETS has special focus on carbon sink offsets projects. By the end of 2020, 2.8 miliion tonnes of forestry offset credit had traded in the Fujian ETS, with a total turnover of over 40 million Chinese yuan, overachieving the province's initial target of forestry offsets target (ICAP, 2021).

National ETS

China's national ETS began operations in June 2021, including 2,225 enterprises in the power sector, and was expected to trade 2.5 billion tons of emission allowances, or 30% of China's national emissions (World Bank, 2021). The launch of national ETS is encouraging, with an average price 52.84 Chinese yuan per ton emission allowances, which is the third highest carbon price after Beijing and Guangdong ETS. The national ETS has now only covered the power sectors for the first compliance year. The legal foundation is relatively weak, there is no specific laws to ensure the market operation. And the emission allowances allocation method of national ETS are mainly based on free allocation or benchmarking, advanced method e.g., auctions shall be introduced to such a large market. Furthermore, details of how to link the regional ETS pilots and national ETS shall be further discussed and published.

Summary

Even though China's ETSs have been in operation for some years, some market design details have not become uniform and finalized. The regional and national markets vary in design, participating industries, allocation methods, trading products, and market threshold. These features isolate the ETS markets from each other. It is important to note that the carbon transactions in the pilots are predominantly intra-provincial. Consequently, while China's regional ETS's have achieved compliance, the price discovery function has not yet matured. Heterogeneous regional markets struggle with carbon price fluctuations, over-allocation of free allowances, low liquidity, and inadequate regulation systems. Emission allowances are mainly issued by free allocation, but the free allocation method has resulted in inefficiencies, political misallocation, and bureaucrat interference.

1.2.2 Academic literature

ETS is an organized market designed to achieve specific policy objectives. In this case, the goal is to limit carbon emissions. The absence of such a mechanism (that is, a lack of market incentives) could let low efficiency continue, delay the adoption of clean energy practices, risk a shortage of energy, and even allow corruption in regulation of emissions. The combination of all that means more pollution. The literature on ETS is growing and maturing. A large number of literature focuses on the European Union Emission Trading Scheme as it was the prototype of other carbon markets (Barrieu and Fehr, 2011; Chevallier et al., 2011; Ibikunle et al., 2016; Lutz et al., 2013; Zeng et al., 2021). Some discuss the New Zealand carbon market (Diaz-Rainey and Tulloch, 2018; Jiang et al., 2009), California Cap-and-Trade (Aguiar-Conraria et al., 2018; Fowlie et al., 2012), and South Korean carbon market (Kim, 2014; Kim et al., 2020). As this study focus on the Chinese emerging carbon markets, this section of literature review concludes the research papers that discuss the carbon markets development in China. Then, briefly summarize the advantages and limitations of the previous empirical studies related to the carbon market integration.

Existing qualitative papers about China's emerging ETS pilot mostly studied the (i) legal basis of the pilot ETS, (ii) allowance allocation methods, (iii) sector coverage, and (iv) political benefits of China's carbon markets, (see among others, Jotzo and Löschel, 2014; Lo, 2016; Stoerk et al., 2019; Zhang and Andrews-Speed, 2020; Zhang, 2015). Zhang et al. (2014) emphasized that a clear legal mandate at the national level is important for developing regional ETS pilots. Financial penalties for non-compliance cannot be altered without building the laws in place. Notably, in the absence of national law, the provinces and sub-provinces would not have strong incentives to engage in emission trading. Zhang (2015) stated that educating the covered entities and ascribing allowances as financial assets are crucial in addition to constructing the market. Stoerk et al. (2019) compares China's carbon markets with EU ETS and California Cap-and-Trade by investigating the literatures and reports, mentioning that the knowledge of the specific details of the China's national ETS has proven elusive. They urged a clarification of details, for instance, nature of the cap, the process of allocation allowances, and an indication of long-term cap trajectory. Hua and Dong (2019) gives an overview of development and current problems in China's carbon markets and discuss the feasibility of future connection among regional carbon markets in China. They summarized that the policy conditions at national or provincial level, trading status, and regional differences between areas have not yet been matured enough to ensure a smooth operation of national markets. A proper direct governmental intervention is indispensable for creating a unified carbon price in China, while allowing differentiated regulatory policies for different regions (Ji et al., 2018). In view of the uncertainties of carbon emissions in China, a set of quantity control tools based on price fluctuations need to be created and be adjusted automatically between quota supply and market price, so as to form a stable price interval with clear expectation consisting of auction reserve price and trigger value. To sum up, the above-mentioned papers concluded that ETS pilots have not yet matured, laws and regulations are not established completely to guarantee a concrete operation of the primary and secondary markets. Hence, carbon secondary prices suffered from the inconsistent standard regionally, the prices are highly fluctuated, no evidence has shown a signal of future unified price (Hua and Dong, 2019), thereby inducing difficulties forming a unified national market.

Stoerk et al. (2019) mentioned that and empirical analysis to the regional ETS pilots are comparatively rarer. Indeed, upon my investigation of empirical studies in this field, not much research has been done on carbon prices relations across ETS pilots, but more on the link between carbon prices and macroeconomics factors and energy markets. For instance, Fan and Todorova (2017) investigated the link between carbon prices and macro risks in China's pilot schemes. Zhang and Zhang (2016) adopted a quantile regression approach to analyse the relationship between energy prices, economics growth, temperature, and Shanghai's carbon price. Chang et al. (2018) investigated the dynamic linkage effects between energy and emission allowance prices for China's regional ETS pilots using cointegration techniques. Wen et al. (2022) examined the driving factors (e.g., stock market, coal and oil price, market sentiment, policy uncertainty, etc.) of China's carbon prices. Limited and few literatures pay attention to linkages between pilots in China. Among the existing ones, Wang et al. (2021) investigated the long run cointegration relation between the EU ETS and China's regional ETS by choosing five regional ETS in China and one EUA price series. They found long-run cointegration among the markets. However, they did not include Shanghai ETS in the analysis, which is an representative pilot in China. Zhao et al. (2020) investigated nonlinear Granger causality and time-varying effect in Chinese ETS pilots; their results show that Guangdong, Hubei, and Shenzhen pilots are time-varying co-movements related to each other. Xiao et al. (2022) calculated the dynamic spillovers of carbon price return among the ETS pilots in China with the connectedness approach; their results suggested that Beijing and Chongqing pilots are the main spillover markets of carbon price returns, while Guangdong and Tianjin are the spillover receivers of the price return. Guo and Feng (2021) applied a generalized forecast error variance decomposition to study the spillovers among China's ETS pilots, their results showed that the dynamics of price in each pilot are driven by its own, supported by the result of below 10% connectedness in the return system.

This paper chooses co-integration and VECM to study the relationship between prices across nine ETS markets, a method that has been used for many years to do research on market integrations and has been successful. Cassel (1918) is considered to be one of the earliest references introducing the concepts of purchasing power parity and the law of one price (LOP). In more recent times, Stigler (1969) conceived of a market as "the area within which the price of a commodity tends to uniformity, allowing for the transportation costs". The application of cointegration methods to the analysis of spatial price relationships has then become common, both to test the LOP and to understand the degree to which different regions/markets are integrated (Goodwin, 1992; McNew and Fackler, 1997). Albeit researchers have argued that the 'cointegration does not imply integration', the relationship between the economics concepts of the LOP and market integration and the statistical concept of cointegration is a complex one. Cointegration and VECM techniques have several limitations and give less information than partial equilibrium market models in which demand and supply equations are stated. Nevertheless, because price data is more frequently available than quantity data in emerging markets, price analysis will be viable in many situations where other methods are not (Fossati et al., 2007). There is a substantial empirical literature concentrated mainly on cointegration and VECM to examine price relationships as a way to investigate market integration. For instance, studies of the price relationship between commodity prices (Ali and Bardhan Gupta, 2011; Ankamah-Yeboah et al., 2017; Fossati et al., 2007; Goodwin, 1992; Papież and Śmiech, 2015), stock market prices integration (Chien et al., 2015; Click and Plummer, 2005; Srivastava et al., 2015; Voronkova, 2004), electricity market integration (Bunn and Gianfreda, 2010; De Vany and Walls, 1999; Gugler et al., 2018; Nepal and Foster, 2016), and carbon market integration (Bredin et al., 2014; Mizrach, 2012; Niblock and Harrison, 2011; Wang et al., 2021). Mizrach (2012) analyses the market architecture and common factors of emission reduction instruments in Europe and North America. This paper provides the most insightful concept regarding our study.

Table 1. Market architecture – Differences among nine ETS in China

	Beijing	Shanghai	Shenzhen	Guangdong	Hubei
Covered Emissions of the Jurisdiction's Total	40%	57%	40%	60%	45%
Number of Regulated Firms	903	298	794	279	338
Involved Industries	Industrial and non-industrial entities; qualified enterprises, and individuals	Airports, chemical fibers, power and heat, water suppliers, hotels, textiles, etc.	Power, water, gas facilities; manufacturing sectors; port and subway sectors; transport sectors.	Power, iron and steel, cement, papermaking, aviation, and petrochemicals	Power and heat supply, iron and steel, metal, etc.
Allocation	Free Allocation; Auctioning up to 5%	Free Allocation; Auctioning	Free Allocation; Auctioning	Free Allocation (95% for power generation, 97% for iron, aviation, and cement); Auctioning	Free Allocation; Auctioning
Carbon Products	BEA, CCER, and Forest Carbon Sinks	SHEA, CCER, and Forest Carbon Sinks	SZEA, CCER, and Forest Carbon Sinks	CDEA, CCER, and Forest Carbon Sinks	HBEA, CCER, and Forest Carbon Sinks
Entry Condition	Over 5,000 tonCO2/year	Over 20,000 tonCO2/year (industrial enterprises); over 10,000 tonCO2/year for other enterprises	Industrial enterprises over 3,000 tonCO2/year, large public building project 10,000 square meters	Over 10,000 tonCO2/year (industrial enterprises); over 5,000 tonCO2/year for service industry	Over 10,000 tonCO2/year energy consumption

Source: Own elaboration based on data from Emission Trading Worldwide: Status Report, by International Carbon Action Partnership, 2020. Retrieved from https://icapcarbonaction.com/en/publications. And from Wind Database. Retrieved from https://www.wind.com.cn/en/edb.html.

Notes: BEA stands for Beijing Emission Allowances, SHEA for Shanghai Emission Allowances, SZEA for Shenzhen Emission Allowances, GDEA for Guangdong Emission Allowances, and HBEA for Hubei Emission Allowances. CQEA, TJEA, FJEA and NEA stands for Chongqing, Tianjin, Fujian, and National emission allowances respectively. CCER stands for China Certified Emission Reduction; it is a carbon offset product that can be traded in regional ETSs. M stands for million. Electricity production of previous regional market participants was covered in regional markets until 2019, after which it transitioned to the national ETS.

Table 1. Market architecture – Differences among regional ETS in China (continued)

	Chongqing	Tianjin	Fujian	National
Covered Emissions of the Jurisdiction's Total	51%	55%	51%	40%
Cap	78.39 MtCO2/year	120 MtCO2/year	126 MtCO2/year	4,500 MtCO2/year (bottom-up)
Number of Regulated Firms	152	139	284	2162
Involved Industries	No pre-define which sectors are covered under its ETS. The power sector was covered until 2019, after which it transitioned to the national ETS	Heat, iron and steel, petrochemicals, chemicals, oil and gas exploration, papermaking, aviation, and building materials	Electricity grid, petrochemical, chemical, building materials, iron and steel, nonferrous metals, paper, aviation, and ceramics	Power, iron and steel, cement, papermaking, aviation, and petrochemicals
Allocation	Free Allocation. Auctioning was introduced in 2021	Free Allocation; Auctioning (twice a year)	Free Allocation (grandfathering and benchmarking)	Free Allocation
Carbon Products	CQEA; CCERs are allowed for up to 8%	TJEA; CCERs are allowed for up to 10% and must have originated from Beijing, Tianjin, or Hebei	FJEA; CCERs are allowed for up to 10%; offsets are restricted to those generated in Fujian province from entities not regulated under the ETS; Hydropower-related credits are not eligible	NEA; CCERs are allowed for up to 5%
Entry Condition	13,000 tCO2 /year or energy consumption of 5000tce/year	20,000 tCO2/year 120 MtCO2	energy consumption of 5,000tce or more in any year from 2013 to 2020	Entities with annual emissions of 26,000 tCO2 in any year over the period 2013-2019.

1.3 Methodology

The co-integration among the CO_2 emissions products of different regional environmental exchanges describes how markets, each of which might be non-stationary, may nonetheless be linked. Engle and Granger (1987) pointed out that most of the macroeconomic variables may be non-stationary through time. It is expected that non-stationary price variables could be bound together and converge to some stationary processes by long-run equilibrium relationships. The multivariate Vector Auto-Regression (VAR) model is a system regression model with multiple endogenous variables; it is a reformulation of the covariance of my data, with two covariances discussed in the model: (i) the covariance between the variables at time t; (ii) the covariance between time t and time $t-h$. This model allows us to analyse both the short-run and long-run dependencies of these variables. The definition of the model starts with the data matrix $x_t = [x_1, x_2, \dots, x_n]'$ where x_t is a $(n \times 1)$ vector of emission allowances prices. The unrestricted VAR *(p)* model was estimated based on the following:

$$x_t = \Pi_1 x_{t-1} + \Pi_2 x_{t-2} + \cdots + \Pi_p x_{t-p} + \varepsilon_t, \quad t = 1, \dots, T, \quad \varepsilon_t \sim IN_p\,(0, \Omega) \qquad (1)$$

$\Pi_1, \Pi_2, \dots, \Pi_p = p \times p$ are coefficient matrices, p denotes the number of lags chosen to ensure no serial correlation in the residual ε_t. Equation (1) shows the reduced form of the model since it described only the variation in x_t as a function of lagged (past) values of the process but failed to capture the current values. This information about current effects in the data is contained in the residual covariance matrix Ω.

Johansen (1988), Johansen and Juselius (1990), and Juselius (2006) used likelihood ratio tests based on a VAR estimation and provided a vector equilibrium correction (VEC) model. This method is estimated by the full information maximum likelihood as suggested in Johansen (1988). The VEC model gives a reformulation of Equation (1) in terms of differences, lagged differences, and levels of the process, which naturally classified the relationship into short-run and long-run effects. Following Johansen (1988), p_t can be appropriately implemented to the error correction model with k-1 lags; and p_t represents a vector of p nonstationary endogenous variables. The error correction formulation for VAR (p) is described as:

$$\Delta x_t = \Gamma_1 \Delta x_{t-1} + \Gamma_2 \Delta x_{t-2} + \cdots + \Gamma_{p-1} \Delta x_{t-p+1} + \Pi x_{t-1} + \varepsilon_t \qquad (2)$$

In Equation (2), the matrix Π contains information about the long-term relationship among endogenous variables, and the rank of $\Pi(\mathrm{r})$ is the error correction (ECM) term, the lag placement of the Error Correction (ECM) term is 1. Either $\Pi = 0$, or it must have reduced the rank: $\Pi = \alpha\beta'$, where α denotes the estimation on the speed of adjustment to the equilibrium, and β denotes the cointegration vectors. Both α and β are $n \times r$ matrices, r is the rank of Π and the number of co-integrating relations, in order to make Equation (2) a stationary process. ε_t is the error term. With the co-integration $\Pi x_{t-1} = \alpha\beta^T x_{t-1}$, the linear combinations $\beta^T x_{t-1}$ should be stationary and could be interpreted as deviations from long-run equilibrium; the matrix α is the adjustment speed coefficients. Thus, the cointegrated VAR (p) model is given by:

$$\Delta x_t = \Gamma_1 \Delta x_{t-1} + \Gamma_2 \Delta x_{t-2} + \cdots + \Gamma_{p-1} \Delta x_{t-p+1} + \alpha\beta' x_{t-1} + \varepsilon_t \quad (3)$$

where $\beta' x_{t-1}$ is the error correction term that shows the long-run relationships between the variables. The likelihood ratio test – the trace test — is used to test the correlations (co-integration rank) between variables, which are shown in Equation (4):

$$\lambda_{trace}(r_0) = -T \sum_{i=r_0+1}^{j} ln\left(1 - \hat{\lambda}_i\right) \quad (4)$$

The null and alternative hypothesis is the number of co-integrating vectors are less or equal to r_0 against a general alternative. The larger the $\hat{\lambda}_i$, the more stationary is the relationship. More specifically, if variables are not co-integrated, the co-integration rank, r_0, equals to zero, and $\ln\left(1 - \hat{\lambda}_i\right) = 0$, λ_{trace} equals to zero. Interventions and market reforms frequently show up in energy markets, especially for early-stage carbon markets, as they are market-driven tools based on policies. This paper uses transitory dummies to account for transitory shocks in the markets, and then the reformulated model is expressed as Equation (5):

$$\Delta x_t = \Gamma_1 \Delta x_{t-1} + \Gamma_2 \Delta x_{t-2} + \cdots + \Gamma_{p-1} \Delta x_{t-p+1} + \alpha\beta' x_{t-m} + \Phi_{tr} D_{tr,t} + \varepsilon_t \quad (5)$$

where the $\Phi_{tr} D_{tr,t}$ is a set of transitory (dummy) variables. Transitory dummies are included to take care of transitory effects to the system cause by specific price shock. Φ_i is the corresponding coefficient (Juselius, 2004). And these transitory shock dummy variables are defined as follows:

$$\Phi_{tr1} = \begin{Bmatrix} -1 \\ 1 \end{Bmatrix}, \Phi_{tr2} = \begin{Bmatrix} 0.5 \\ -1 \\ 0.5 \end{Bmatrix}, \Phi_{tr3} = \begin{Bmatrix} 0.5 \\ 1 \\ 0.5 \\ -2 \end{Bmatrix},$$

$$\Phi_{tr4} = \begin{Bmatrix} -1 \\ -0.5 \\ 0.5 \\ 1 \end{Bmatrix}, \Phi_{tr5} = \begin{Bmatrix} 1 \\ -0.5 \\ -0.5 \end{Bmatrix}, \Phi_{tr6} = \begin{Bmatrix} 0.5 \\ 0.5 \\ 0.5 \\ 0.5 \\ -2 \end{Bmatrix} \quad (6)$$

The important fact of transitory dummies is that they sum to zero over time, so they do not have any effect on asymptotic distributions on the trace tests. It turns out later that there are six events where we need the six transitory dummies, and they will be defined when we use them (see section 1.6.1 below). The VAR (p) model can be given different parametrizations without imposing any binding restrictions on the model parameters and multicollinearity effects would present in those time-series data. There are tests available to test one at a time whether a specific variable does not belong to the co-integrating vector. For instance, if we want to perform this restriction test for Beijing emission allowances prices, then the beta would look like zero while the other betas remain the same. Thus, the long-run exclusion tests are conducted, these tests on restrictions on beta are done for a given choice of rank. If the restrictions are accepted, the variable can be omitted from the long-run relations, and the VAR model can be reformulated without losing information. The test of the same restriction on all beta is given in Juselius (2006), Section 7.2. For a test of long-run exclusion of one variable or two variables in the co-integration relations for $x_t^{'} = [BEAPrice_t, SHEAPrice_t, GDEAPrice_t, HBEAPrice_t, SZEAPrice_t]$, the hypothesis is:

$$\mathcal{H}_1: \beta^{'} = H \times \varphi = 0 \qquad (7)$$

where $\beta^{'}$ is $p1 \times p1$, H is $p1 \times s$, φ is an $s \times r$ matrix of the unrestricted coefficients; and s is the number of unrestricted coefficients in each vector, $p1$ is the dimension of $x_{t-1}^{'}$ in the VAR model.

1.4 Data

To assess the nature of China's carbon markets, this paper obtains the daily settlement price of spot emission allowances products from nine ETS - Beijing, Chongqing, Fujian, Guangdong, Hubei, Shanghai, Shenzhen, Tianjin, and national ETS in China, sourced by Wind Database. It is worth noting that the scarcity of empirical research on these pilots maybe due to the inactive trading, hence data are less available. Zero trading volume exist in each price series, which means no price data are available for those days. The reason behind might be due to the absence of supportive legislation, which result in a less interest of enterprises to participate carbon trading; or the local governments have relaxed the emission restrictions hence decrease the demand of emission products (Guo and Feng, 2021; Xiao et al., 2022). In this regard, I agree with Fan and Todorova (2017), the main challenge in analysing carbon price dataset from China's ETS is the large number of missing values that indicate little or no trading activity. After considered the availability and quality of the daily price data in each ETS, I use two sets of data to proceed.

First, I focus on five markets[5] – Beijing, Guangdong, Hubei, Shanghai, and Shenzhen ETS. The dataset 1 includes five monthly price series that ranges from 28 April to 25 December 2019. The above chosen markets are the five largest ETS in market size in China which have longer trading history that allows the paper to extend the sample period (Chang et al., 2018; Zhang, 2015b). Tests are conducted at a monthly level, upon investigation, Beijing ETS has 512/1436, Shanghai ETS has 603/1436, Guangdong ETS has 241/1436, Shenzhen ETS has 107/1436, and Hubei ETS has 23/1436 missing daily data during the sample period. Hence, I transformed the daily data to monthly frequency by calculating the mean price of the month, resulting in total of 69*5 observations. The transformation from daily data to monthly data is consistent with Wang et al. (2021).

The dataset 2 covers all ETS - Beijing, Chongqing, Fujian, Guangdong, Hubei, Shanghai, Shenzhen, Tianjin, and national ETS in China with the use of daily prices between 16 July 2021 and 15 July 2022. The shorter horizon of dataset 2 is mainly due to the national ETS became operation only since 16 July 2021. Meanwhile, Fujian, Chongqing, and Tianjin ETS both are growing to be more mature in 2021 and 2022 (with growing trading volume and active trading). At this point, it is fruitful to examine the dynamics of nine carbon prices in from all ETS after one year of operation of national ETS. Descriptive statistics for emission allowances prices are presented in Table 2. Monthly prices of emission allowances of five regional ETS in China are provided in Fig. 1. Daily prices of emission allowances of nine ETS from July 2021 to July 2022 provided in Fig. 2.

[5] Another three regional ETS, Fujian, Tianjin, and Chongqing either have smaller market size and lower liquidity (Tianjin and Chongqing ETS) or shorter history (Fujian). Although Tianjin and Chongqing started trading in 2013/2014, the two ETS both have and insufficient trading volumes for the first five years' (2014-2019) operation (916 days of no trading for Chongqing ETS and 975 days for Tianjin). Hence, it is meaningless to include Tianjin and Chongqing in dataset 1.

Figure 1. Emission allowances prices from five regional ETSs from 2014.04 – 2019.12

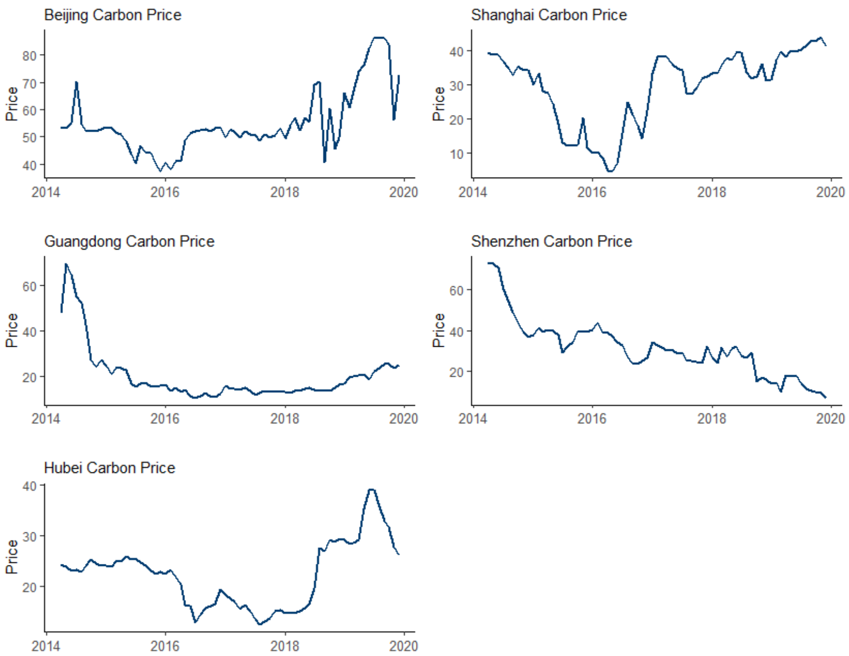

Figure 2. Emission allowances prices from nine regional ETSs from 2021.07 – 2022.07

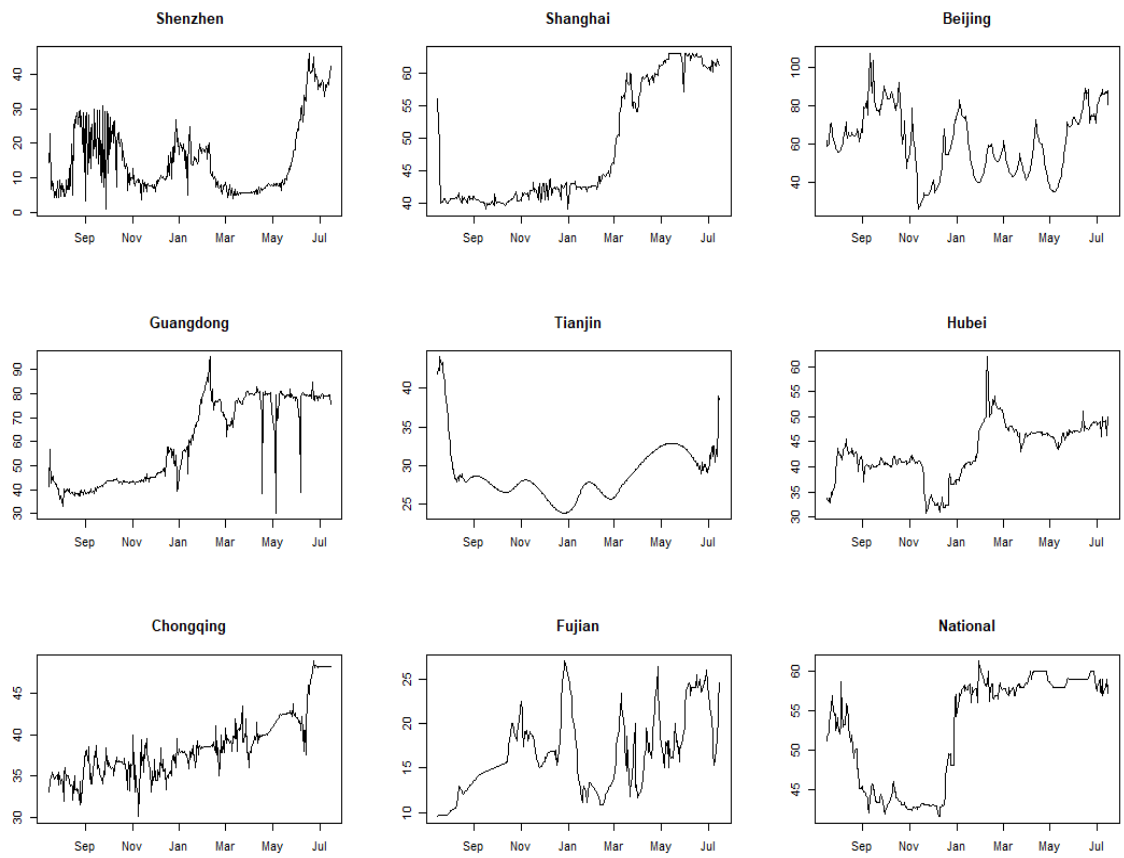

Figure 1 shows some sharp reductions, and some potential outliers exist in the series (third panel), signaling these series are more deterministic than stochastic. Given the policy-driven nature of these carbon markets, the practical implementation issues, such as the change of total cap setting, allocation method of emission allowances, and offsetting mechanism, will result in price fluctuations. Hubei ETS has maintained the most consistent price and volume since its launch in 2014 (see Figure 1), confirmed by the smallest standard deviation value, showing lower market volatility. It is observed that as regional carbon markets approached the compliance period, secondary market trading increased significantly, with carbon allowance spot prices falling to varying degrees.

Table 2. Descriptive statistics of allowances prices in regional ETS

Panel A - monthly prices from five markets, from 28 April 2014 to 25 December 2019						
Statistic	Min	Mean	Max	St.Dev	Skew.	Kurt.
Beijing	37.30	55.00	86.80	11.87	1.22	1.04
Shanghai	4.70	29.70	44.00	10.86	-0.92	-0.32
Guangdong	10.40	19.70	69.70	12.17	2.51	5.89
Shenzhen	7.00	31.30	72.80	13.99	0.88	1.44
Hubei	12.50	22.40	38.90	6.50	0.46	-0.32
Panel B - daily prices from nine markets, from 16 July 2021 to 15 July 2022						
Statistic	Min	Mean	Max	St.Dev	Skew.	Kurt.
Beijing	26.17	61.04	107.30	15.71	0.10	-0.83
Chongqing	30.00	38.47	49.00	3.86	0.95	0.69
Guangdong	30.28	60.08	95.26	17.28	0.04	-1.70
Fujian	9.53	16.68	27.00	4.30	0.46	-0.58
Hubei	30.79	43.13	61.89	5.40	-0.25	-0.13
Shanghai	39.00	48.43	63.00	9.14	0.58	-1.49
Shenzhen	1.00	15.38	46.00	10.17	1.07	0.20
Tianjin	23.89	29.00	44.00	3.60	1.67	4.03
National	41.46	52.84	61.38	6.83	-0.52	-1.49

Source: Own elaboration based on data from Wind Database. Min. denotes Minimum price in the period. Max denotes maximum price in the period. St.Dev. denotes standard deviation of the series. Skew. Means skewness while Kurt. Means kurtosis. Missing data were supplemented by Kalman Smoothing (Moritz and Bartz-Beielstein, 2017) since it provides minimum mean square error estimation and linear interpolation.

The Beijing carbon market experienced light trading following the compliance period that ended on 31 August 2018, with the average price falling by 20 (Chinese yuan) in September 2018 compared to August 2018. Between April and October 2014, the price of Guangdong emission allowances fell significantly due to a change in the minimum price setting in the carbon primary market. In September 2014, the Guangdong carbon market adjusted the reserve price for the primary market auction of carbon allowances from 60 (Chinese yuan) to 25 (Chinese yuan). This significant adjustment mobilized the auction, which resulted in the secondary market price also falling to the reserve price level of the primary market auction due to the greater volatility of the auction reserve price compared to 2013.

As for dataset 2 (shown in Table 2 Panel B), Beijing's average carbon price remains the highest among all ETS, while Shenzhen has the lowest average price. Even an increase trend of Shenzhen prices is observed from dataset 2, it is not comparable to the large price decrease that has happened in Shenzhen ETS during 2014-2019, hence the price of Shenzhen ETS stays low. Observed from the standard deviation, Guangdong ETS price has the largest values in both datasets, meaning that Guangdong ETS prices are the most volatile among all. Chongqing and Tianjin are less volatile in the price dataset 2. This view is different from Guo and Feng (2021) that shows Chongqing ETS shows larger fluctuations during June 2014 and June 2020. Intuitively, the evidence shows that Chongqing ETS is developing to be more stable, and further confirms the need of including Chongqing ETS in the sample. Most prices, apart from Shenzhen and Tianjin, are with negative value of kurtosis which indicates the distribution has lighter tails than the normal distribution. And as for skewness, the National ETS and Hubei ETS are left skewed while all others show longer tail on the right.

1.5 Results and discussions

In this section, the empirical results are presented and discussed. Subsection 1.6.1 shows the results for dataset 1, and subsection 1.6.2 presents the empirical results for dataset 2.

1.5.1 Five major ETS in China

The model in this section is based on the monthly average price, with 69 observations from five regional ETS – Beijing, Guangdong, Hubei, Shanghai, and Shenzhen. The first diagnostic test of the co-integrated VAR model is to test for stationarity of the spot prices from regional ETSs by using the augmented Dicky-Fuller test (Dickey and Fuller, 1979), KPSS test (Kwiatkowski et al., 1992), and Zivot unit root test (Zivot and Andrews, 1992). The stationary tests confirmed that five monthly series are both nonstationary, but stationary in their first difference representations [6]. In addition, the price series are highly persistent in the sense that autocorrelation decays to zero very slowly. Slow-decaying autocorrelation is considered as the

[6] The results of stationary tests are provided in Table A3 in Appendix A.

signal for non-stationary time series[7]. Thus, I conclude the variables are non-stationary and integrated of the same order, I (1).

Johansen's likelihood ratio tests for co-integration are sensitive to the lag length specification in the VAR model. The proper lag length at a VAR model should be determined to prevent spurious regression. To check the robustness of the results to the lag length specification, I test the regression with lag 1, lag 2, lag 3, and lag 4 in the VAR model instead of automatically choosing by information criteria in the econometric software[8]. In conclusion, lag 2, shown as VAR(2), is chosen.

However, the additive outliers in the series would be a reason that decreases the quality of the model. According to Equation (5), the inclusion of some transitory shock dummies is considered in the model to capture the impact of policy changes in regional ETSs. The six added dummy variables are included in the deterministic terms D_{tr}, and they are retained if they generate significant p values in the ARCH test, Serial test, and the normality test statistics. To account for the price fluctuation around the compliance deadline in Beijing and Guangdong ETS, Φ_{tr1} is included; Φ_{tr2} and Φ_{tr3} account for price fluctuations in Shanghai ETS; Φ_{tr5} and Φ_{tr6} account for price fluctuations in Guangdong and Hubei ETS respectively. Additionally, Φ_{tr4} is included to account for the carbon primary market floor price change in August 2014 — from 60 (Chinese) yuan/ton to 25 (Chinese) yuan/ton in Guangdong ETS. As such, six outlier dummies are defined:

Φ_{tr1} = 1 for t = 2018;09 , -1 for 2018:08, 0 otherwise for Beijing ETS price. And Φ_{tr1}= 1 for t = 2015;06, -1 for 2015;05, 0 otherwise for Guangdong ETS price.

Φ_{tr2} = -1 for t = 2015;11, 0.5 for 2015:10 and 2015:12, 0 otherwise for Shanghai ETS price.

Φ_{tr3} = 0.5 for t = 2016;04, 1 for 2016:05, 0.5 for 2016:06, and -2 for 2016:07, 0 otherwise for Shanghai ETS price.

Φ_{tr4} = -1 for t = 2014;08, -0.5 for 2014:09, 0.5 for 2014:10, 1 for t = 2014;11, 0 otherwise for Guangdong ETS price.

Φ_{tr5} = 1 for t = 2019;03, 0.5 for 2019:04 and 2019:05, 0 otherwise for Shenzhen ETS price.

Φ_{tr6} = -2 for t = 2018;08, 0.5 for 2018:04 -2018:07, and 2019:05, 0 otherwise for Hubei ETS price.

After inclusion of transitory shock dummies, diagnostic tests[9] are performed to check the quality of the VAR model. It reveals that with the inclusion of six transitory dummies, the ARCH

[7] Results of autocorrelations in the time series are provided in Figure A2 in Appendix A.

[8] Normality tests for lag selection are provided in Table A4 in Appendix A.

[9] Tests results see, Table A4 Panel B in Appendix A.

test, serial test, and skewness tests are improved, especially for VAR (1) and VAR (2). The null hypothesis of no autocorrelation cannot be rejected for VAR (1) and VAR (2) at 5% level. The VAR (2) model is the only one model that cannot reject the null hypothesis of zero skewness at 1% level. In general, the model is well-specified; only the normality of the series is not fulfilled. Considering the nature of the deterministic price series (rather than stochastic) and relatively small data sample, this is acceptable. Therefore, we proceed with tests with two lags and six dummies.

1.7.1.1 Estimations of long-run co-integration relationships

Next, I perform the Johansen cointegration test using the trace statistics in order to test for the cointegration rank. The results are presented in Table 3 below. It is clear that there is some evidence for cointegration in the sample period. In Table 3, the null hypothesis $r = 0$ gives a trace statistic of 76.58, which is significant at the 5% level. Thus, the null hypothesis of no co-integration is rejected. And the null hypothesis of $r \leq 1$ is not rejected at both 5% and 10% level as the trace test statistic is $43.62 < 45.23$. To conclude, the co-integrating tests above indicate that the rank is one. These results exhibit that emission prices of regional ETS pilots in China have equilibrium relationships in long term, but in the short term the five variables can be in disequilibrium. The long-run and short-run dynamic structure can be expressed as a VEC model. Thus, on the premise of the existence of one co-integration relationship, the VEC model can be further conducted.

Table 3. Results of the Johansen co-integration unrestricted test

Null hypothesis	Alternative hypothesis	T statistic (with 6 dummies)	Critical value 5% level	Critical value 10% level
Trace statistics				
$r = 0$	$r > 0$	76.58**	70.60	66.49
$r \leq 1$	$r > 1$	43.62	48.28	45.23
$r \leq 2$	$r > 2$	23.16	31.52	28.71
$r \leq 3$	$r > 3$	5.96	17.95	15.66
$r \leq 4$	$r > 4$	0.08	8.18	6.5

*Notes: Monthly frequency. ** Denotes rejection of the null hypothesis at 0.05 level; * denotes rejection of the null hypothesis at 0.1 level. The first column in the table shows the null hypothesis.*

To investigate the long-run co-integration relationship between emission allowances prices in regional ETSs, a VEC model is performed with rank one. Since the cointegration determines whether the five carbon markets have a long-run relationship, their coefficients in the cointegrating vector reveals that how the markets are related in the long run. As Xiao et al. (2022) examined in their study, Guangdong ETS is significantly affected by external spillover from other ETS in China. The reported cointegrating vectors are normalized around Guangdong ETS. Its cointegrating vectors might be usefully interpreted in that context. Hence, normalizing the co-integrating vector on Guangdong ETS prices, the estimated co-integrating coefficients are shown in Table 4 below.

Table 4. The restricted estimate of the co-integrating vectors β for r =1

Co-integrating Equations	Coef. ($\hat{\beta}$)
GDEAPrice (-1)	1.000
BEAPrice (-1)	0.101
SHEAPrice (-1)	-0.450
SZEAPrice (-1)	-0.171
HBEAPrice (-1)	-0.877
AIC	-1403.637
BIC	-1240.49
Log likelihood	300.474

Notes: Monthly frequency. Data are normalized to Guangdong emission allowances price.

The co-integration equation can be expressed as Equation (8):

$$LGDEAPrice_{t-1} = -0.101 \times LBEAPrice_{t-1} + 0.45 \times LSHEAPrice_{t-1} + 0.171 \times LSZEAPrice_{t-1} + 0.877 \times LHBEAPrice_{t-1}, \quad (8)$$

As shown in Equation (8), the price of Beijing ETS shows negative relationship to Guangdong ETS while Shanghai, Shenzhen, and Hubei show positive to Guangdong ETS. It suggests that a 1% decrease in the Beijing ETS price lowers the price of Guangdong ETS by 0.101%. Similarly, a 1% increase in prices of Shanghai, Shenzhen, and Hubei ETS, increases the Guangdong ETS price by 0.450%, 0.171%, and 0.877%, respectively. The rather large coefficients, 0.450% (0.877%) for Shanghai (Hubei), appear reasonable because they suggest that Guangdong is heavily influenced by the larger market (Hubei and Shanghai ETS). Hubei is the largest provincial ETS in China in terms of active trading and market size. Shanghai ETS covers 57% of the total emission in the jurisdiction while another two citywide ETS, Beijing and Shenzhen, covers 24% and 40%, respectively.

It is interesting that price of Guangdong ETS is inversely related the price of Beijing ETS. It means that a shock which is favorable for Beijing ETS might be unfavorable for Guangdong ETS, hence such negative results is produced. Shocks related to interprovincial trade channels are likely to provide part of the explanation. Beijing depends heavily on imports from other provinces, particularly the import of resources and materials produced by secondary and tertiary industries, while Guangdong province is the one of the largest exporters in inter-provincial trade (Chen et al., 2021; Meng et al., 2016). The story of inter-provincial cannot be conclusive enough as Shanghai also outsourced half of its electricity but is empirically positively related to Guangdong ETS. To further complicate the interactions, Shanghai imports renewable energy, such as hydropower mainly from western China. Geographically, Beijing is the farthest ETS from Guangdong among all region ETS in China, significant physical distance and difference in energy, weather condition, and market design can be another explanation for the negative long run relationship between the two markets.

However, at this stage it is not clear whether all of the five prices are significantly in the long-run equilibrium relation. The Johansen and Juselius procedure allow for testing several hypotheses on the coefficients by imposing restrictions. Thus, a restricted VECM is implemented to estimate the long-run impacts. The long-run exclusion tests are therefore conducted to check whether a variable included in the VEC model can be omitted in the long-run relationship. Coefficient estimates and significance levels associated with the tests of zero restrictions are shown in Table 5. The rejection of the null hypothesis means that the variable should be added to the co-integrating equation.

According to Table 5, the hypothesis of long-run exclusion cannot be rejected for both Beijing and Shenzhen emission allowances prices with p-value as high as respectively 0.90 and 0.59. A joint test $\mathcal{H}6$ also fails to reject the null that both Beijing and Shenzhen emission allowances price variables are not in the co-integration relation ($\chi^2(2)$ = 0.78, p-value = 0.68). The hypothesis $\mathcal{H}2,\ \mathcal{H}3\ , and\ \mathcal{H}5$ are all rejected at 5% level; these results reveal that the long-run exclusion of Shanghai, Guangdong, and Hubei emission allowances prices in the co-integration relations are rejected.

Thus, we concluded that Beijing and Shenzhen's allowances prices can be omitted in the long-run relation. Now it is clear that each percentage-point increase in the Shanghai emission allowances price will cause the decrease of 0.3712% in the Guangdong price, which is significant; and each percentage-point increase in Hubei emission allowances price will cause the decrease of 0.7801% in the Guangdong price significantly. In conclusion, there is long-run cointegration found in China's ETS pilot, but Beijing and Shenzhen ETS have been excluded in the long-run relation. Both Shanghai and Hubei ETS are in the long run relation and showed negative relation to Guangdong ETS's prices.

Table 5. Tests of same restriction on all co-integration relations (r=1)

	Beijing	Shanghai	Guangdong	Shenzhen	Hubei
β_1'	0.101	-0.450	1.000	-0.171	-0.877
Restricted estimates					
$\boldsymbol{\mathcal{H}1}$: $\beta_{BEAPrice} = 0$ $\mathcal{X}^2(1) = 0.02$ $[p = 0.9]$ $\mathcal{H}1$ not rejected: Beijing can be excluded					
$\beta_1^{c\prime}$	0.000	-0.4323	1.000	-0.1956	-0.867
$\boldsymbol{\mathcal{H}2}$: $\beta_{SHEAPrice} = 0$ $\mathcal{X}^2(1) = 4.64$ $[p = 0.03]$ $\mathcal{H}2$ rejected at 5% level					
$\beta_1^{c\prime}$	-0.8701	0.000	1.000	-0.021	-0.666
$\boldsymbol{\mathcal{H}3}$: $\beta_{GDEAPrice} = 0$ $\mathcal{X}^2(1) = 3.56$ $[p = 0.00]$ $\mathcal{H}3$ rejected at 5% level					
$\beta_1^{c\prime}$	1.000	-0.130	0.000	0.367	-0.0234
$\boldsymbol{\mathcal{H}4}$: $\beta_{SZEAPrice} = 0$ $\mathcal{X}^2(1) = 0.29$ $[p = 0.59]$ $\mathcal{H}4$ not rejected: Shenzhen can be excluded					
$\beta_1^{c\prime}$	0.478	-0.490	1.000	0.000	-0.8778
$\boldsymbol{\mathcal{H}5}$: $\beta_{HBEAPrice} = 0$ $\mathcal{X}^2(1) = 6.27$ $[p = 0.01]$ $\mathcal{H}5$ rejected at 5% level					
$\beta_1^{c\prime}$	1.8845	-0.511	1.000	1.198	0.000
$\boldsymbol{\mathcal{H}6}$: $\beta_{BEAPrice} = \beta_{SZEAPrice} = 0$ $\mathcal{X}^2(2) = 0.78$ $[p = 0.68]$ $\mathcal{H}6$ not rejected: Beijing and Shenzhen can be excluded					
$\beta_1^{c\prime}$	0.000	-0.3712	1.000	0.000	-0.7801

Notes: The null hypothesis is H_0: a restricted linear combination of the vector process is stationary while the alternative hypothesis H_1 shows a non-stationary system, In order to test $\beta_{GDEAPrice} = 0$, we normalized the co-integrating vector on Beijing ETS price in $\mathcal{H}3$

1.7.1.2 Estimations of short-run co-integration relationships

To focus on examining the short-run dynamics of the linkage effects among the five markets, the corresponding VECM is estimated for changes in the emission allowances prices. Table 8 provides the result of the analyses.

In summary, Beijing's, Hubei's, and Guangdong's emission allowances prices remain unaffected by any short-term effect from other regional ETS pilots. Both Shanghai and Shenzhen seem to be led by changes in lagged Beijing emission allowances prices. The lagged emission allowances prices in the Beijing and Hubei ETS pilots have significant impact on their current emission allowances prices.

Table 6. Estimation of the short-run and long-run equation

Coefficients	ΔBeijing	ΔShanghai	ΔGuangdong	ΔShenzhen	ΔHubei
Error Corrections	-0.0023	0.0657	**-0.2169*** **	0.0446	-0.0079
	(0.0468)	(0.0743)	(0.0425)	(0.0593)	(0.0320)
	[-0.050]	[0.885]	[-5.107]	[0.752]	[-0.246]
ΔBeijing (-1)	**-0.4606*** **	**0.3703** **	0.0801	**0.4026*** **	-0.0540
	(0.1102)	(0.1749)	(0.1000)	(0.1395)	(0.0753)
	[-4.180]	[2.117]	[0.801]	[2.885]	[-0.717]
ΔShanghai (-1)	-0.0823	0.1712	0.0859	-0.0008	0.0715
	(0.0725)	(0.1150)	(0.0657)	(0.0918)	(0.0495)
	[-1.135]	[1.489]	[1.307]	[-0.009]	[1.444]
ΔGuangdong (-1)	0.1416	0.1817	-0.0320	0.1974	0.0183
	(0.1160)	(0.1841)	(0.1052)	(0.1469)	(0.0793)
	[1.221]	[0.987]	[-0.304]	[1.344]	[0.230]
ΔShenzhen (-1)	-0.0169	0.1175	-0.0243	**-0.1991***	0.0835
	(0.0898)	(0.1426)	(0.0815)	(0.1137)	(0.0614)
	[-0.188]	[0.824]	[-0.298]	[-1.750]	[1.360]
ΔHubei (-1)	-0.1604	-0.4160	-0.1413	0.3823	**0.3998*** **
	(0.1959)	(0.3109)	(0.1777)	(0.2481)	(0.1340)
	[-0.819]	[-1.338]	[-0.795]	[1.541]	[2.985]
Adjusted R-squared	0.3636	0.3215	0.2811	0.3035	0.21
Residual standard error	0.1083	0.1719	0.09825	0.1372	0.07406
F-statistic	3.734 on 14 and 53 DF	3.268 on 14 and 53 DF	2.871 on 14 and 53 DF	3.085 on 14 and 53 DF	2.272 on 14 and 53 DF

*Notes: Monthly frequency. The six transitory dummies are still in the model, they are just not shown in the result. *** Significant at the 1% level, ** significant at the 5% level, * significant at the 10% level. T-statistics in square brackets []; Standard Error in parentheses ().*

The findings lead to the following considerations: (1) the rank one of cointegration among five jurisdictions is very low and far from achieving a single carbon price in China. The generally low level of co-integration in China's ETS pilots within the sample period may be due to the isolated trading by design, as well as choices of sector coverage and market threshold in each pilot. However, there is a slight indication that the cointegration rank might be two, so there is potential a more robust integration of these markets in the near future. (2) The regional market prices are still dominated by local effects. (3) Shanghai, Guangdong, and Hubei are co-integrated in the long run, increases in Shanghai and Hubei prices will cause decrease of price in Guangdong. (4) The results from this study provide important insights for market participants, especially for institutional and individual investors. In particular, for investors interested in the Shanghai ETS and Shenzhen ETS, using historical information containing the change in Beijing ETS might be a way to improve the short-run forecasting of future carbon prices.

1.5.2 Nine ETS in China

This subsection reports the empirical results examined in dataset 2, which contains nine ETS markets in China, ranging from July 2021 to July 2022. The model is based on dataset 2 (see Section 1.5), with 365 observations from Beijing, Chongqing, Fujian, Guangdong, Hubei, Shanghai, Shenzhen, Tianjin, and National ETS system. Upon checking, the nine time series are both non-stationary, but stationary in their first difference representations, tests results are reported in Table A5 in Appendix A. Thus, I conclude the variables are non-stationary and integrated of the same order, I (1). Then, Johansen's likelihood ratio tests for co-integration are sensitive to the lag length specification in the VAR model. The proper lag length 4, selected by AIC test is chosen. The plots of structural stability of a VAR(4) for dataset 2 is reported in Figure A3 in Appendix A. In conclusion, the paper moves forward with four lags. Having established the stationarity tests for the data and identified the length of the lag. I move forward with the examination of Johansen cointegration test with trace statistics. The cointegration test results are presented in Table 7 below.

Table 7. Results of the Johansen co-integration unrestricted test

Null hypothesis	Alternative hypothesis	T statistic	Critical value 5% level	Critical value 10% level
$r = 0$	$r > 0$	242.33***	192.84	186.5
$r \leq 1$	$r > 1$	168.78**	157.11	151.4
$r \leq 2$	$r > 2$	119.19*	124.25	119.0
$r \leq 3$	$r > 3$	76.28	90.39	85.2
$r \leq 4$	$r > 4$	52.65	70.60	66.5
$r \leq 5$	$r > 5$	34.28	48.28	45.2
$r \leq 6$	$r > 6$	20.92	31.52	28.7
$r \leq 7$	$r > 7$	8.22	17.95	15.7
$r \leq 8$	$r > 8$	2.47	8.18	6.5

*Notes: Daily frequency. *** Denotes rejection of the null hypothesis at 0.01 level . ** Denotes rejection of the null hypothesis at 0.05 level; * denotes rejection of the null hypothesis at 0.1 level. The first column in the table shows the null hypothesis.*

Similar as subsection 1.6.1.1, I first examine i) whether the nine markets are cointegrated? And ii) If cointegrated, how many cointegrating relationships exist? Focusing on the results reported in Table 7, it is observed that the null hypothesis r=0 gives a trace statistic of 242.33, which is significant at 1% level. Thus, the null hypothesis of no cointegration relation is rejected significantly, answer to the first question is yes, nine markets are cointegrated. Then, the null hypothesis of r ≤ 1 is rejected at 5% level since test statistic 168.78 > 157.11, the null hypothesis of r ≤ 2 is rejected at 10% level as the test statistics 119.0 <119.19<124.25, and null hypothesis of r ≤ 3 cannot be rejected at both 5% and 10% level. Three cointegrating vectors and six common I(1) trends are observed. So, to conclude, the rank of the cointegrating relationship among nine ETS shows three. Based on the results of trace tests reported in Table 7, there are three cointegrating relations and six common trends respectively. The results indicate that within this vector of markets there are more common trends than cointegrating relations, it can be further interpreted as evidence of partial convergence among the nine markets. Moreover, the results reported in Table 7 show a higher degree of market integration than those reported in Table 4. The cointegrating relationship (from 2021 to 2022) is observed to be more than that of the relationship in five markets (2014 to 2019), which means the markets are more integrated than before. This more favorable result could be attributable to the analysis's use of the most recent data sample (2021-2022) and the inclusion of a more ETS markets.

To investigate the long-run co-integration relationship between emission allowances prices in regional ETSs, a VEC model is performed with rank three. To understand how the national ETS interacts with other ETS market in a long run, the reported cointegrating vectors are normalized around National ETS. The estimated co-integrating coefficients are shown in Table 8 below.

Table 8. The restricted estimate of the co-integrating vectors β for r =3

Co-integrating Equations	Coef. ($\hat{\beta}$)
NEAPrice (-1)	1.00
BEAPrice (-1)	$-2.22*10^{-17}$
FJEAPrice (-1)	$1.11*10^{-16}$
CQEAPrice (-1)	15.14
HBEAPrice (-1)	2.95
SZEAPrice (-1)	-1.02
TJEAPrice (-1)	-5.94
SHEAPrice (-1)	-1.30
GDEAPrice (-1)	-3.52

Notes: Daily frequency. Data are normalized to National ETS. NEAPrice stands for National Emission allowances price. GDEA, BEA, CQEA, FJEA, HBEA, SHEA, SZEA, and TJEA stands for Guangdong, Beijing, Chongqing, Fujian, Hubei, Shanghai, and Tianjin Emission Allowances prices, respectively.

The co-integration equation can be expressed as Equation (9) below:

$$LNEAPrice_{t-1} = 3.52 \times LGDEAPrice_{t-1} + 2.22 * 10^{-16} \times LBEAPrice_{t-1} - 15.14 \times LCQEAPrice_{t-1} - 1.11 * 10^{-16} \times LFJEAPrice_{t-1} - 2.95 \times LHBEAPrice_{t-1} + 1.30 \times LSHEAPrice_{t-1} + 1.02 \times LSZEAPrice_{t-1} + 5.94 \times LTJEAPrice_{t-1} \quad (9)$$

As shown in Equation (9), the price of Chongqing ETS, Fujian ETS, and Hubei ETS are negatively related to the National ETS in a long run, while all the other ETS have positive relationship with the National ETS. The national ETS is less affected by changes in Beijing and Fujian ETS, as the coefficients for Beijing and Fujian ETS are very small. Larger coefficients appear in Chongqing and Tianjin ETS which suggest that national ETS is heavily influenced by these two ETS (Chongqing and Tianjin). A 1% increase in Chongqing and Hubei ETS decreases the National ETS price by 15.14% and 2.95% respectively. However, a 1% increase in Guangdong, Shanghai, Shenzhen, and Tianjin ETS is associated with a decrease of 3.52%, 1.30%, 1.02%, and 5.94%, respectively in the national ETS.

Finally, the long-run exclusion tests are conducted to check whether all the variables are significantly included in the VEC model. Coefficient estimates and significance levels associated with the tests of zero restrictions are shown in Table 9. The rejection of the null hypothesis means that the variable should be added to the co-integrating equation.

Table 9. restriction tests for long-run cointegrating relations (r=3)

	NEA	BJEA	FJEA	CQEA	HBEA	SZEA	TJEA	SHEA	GDEA
$\beta_1^{'}$	1.00	$-2.22*10^{-17}$	$1.11*10^{-16}$	15.14	2.95	-1.02	-5.94	-1.30	-3.52
$\beta_2^{'}$	-0.28	$-1.11*10^{-16}$	$2.78*10^{-17}$	-4.30	-0.84	0.29	1.69	0.37	1.00

Restricted estimates (normalized to National ETS)

$\boldsymbol{\mathcal{H}7}$: $\beta_{BJEAPrice} = 0$ $\mathcal{X}^2(1) = 14.8$ $[p = 0.00]$ $\mathcal{H}6$ rejected. Beijing cannot be excluded

$\boldsymbol{\mathcal{H}8}$: $\beta_{FJEAPrice} = 0$ $\mathcal{X}^2(1) = 29.06$$[p = 0.00]$ $\mathcal{H}7$ rejected. Fujian cannot be excluded

$\boldsymbol{\mathcal{H}9}$: $\beta_{CQEAPrice} = 0$ $\mathcal{X}^2(1) = 27.05$ $[p = 0.00]$ $\mathcal{H}8$ rejected. Chongqing cannot be excluded

$\boldsymbol{\mathcal{H}10}$: $\beta_{HBEAPrice} = 0$ $\mathcal{X}^2(1) = 21.46$ $[p = 0.00]$ $\mathcal{H}9$ rejected. Hubei cannot be excluded

$\boldsymbol{\mathcal{H}11}$: $\beta_{SZEAPrice} = 0$ $\mathcal{X}^2(1) = 17.59$ $[p = 0.00]$ $\mathcal{H}10$ rejected. Shenzhen cannot be excluded

$\boldsymbol{\mathcal{H}12}$: $\beta_{TJEAPrice} = 0$ $\mathcal{X}^2(2) = 25.4$ $[p = 0.00]$ $\mathcal{H}11$ rejected. Tianjin cannot be excluded

$\boldsymbol{\mathcal{H}13}$: $\beta_{SHEAPrice} = 0$ $\mathcal{X}^2(2) = 20.75$ $[p = 0.00]$ $\mathcal{H}12$ rejected. Shanghai cannot be excluded

$\boldsymbol{\mathcal{H}14}$: $\beta_{GDEAPrice} = 0$ $\mathcal{X}^2(2) = 31.75$ $[p = 0.00]$$\mathcal{H}13$ rejected. Guangdong cannot be excluded

Restricted estimates (normalized to Guangdong ETS)

$\boldsymbol{\mathcal{H}15}$: $\beta_{NEAPrice} = 0$$\mathcal{X}^2(2) = 1.23$ $[p = 0.75]$ $\mathcal{H}14$ cannot be rejected. National ETS can be excluded

Notes: In order to test $\beta_{NEAPrice} = 0$*, we normalized the co-integrating vector on Guangdong ETS price in* $\mathcal{H}15$.

According to the result from Table 9, $\mathcal{H}7 - \mathcal{H}14$ are all rejected, which means all nine prices cannot be omitted while normalized to Guangdong ETS. However, to test whether the national ETS itself is significantly in the long-run relation. I re-normalized the model to Guangdong ETS. Then, surprisingly, $\mathcal{H}14$ cannot be rejected, hence the national ETS can be omitted in the long run relation. Thus, I re-write the co-integration equation, excluded the national ETS and normalized to Guangdong ETS price as follow:

$$LGDEAPrice_{t-1} = -0.23 \times LBEAPrice_{t-1} - 0.33 \times LFJEAPrice_{t-1} + 1.93 \times LCQEAPrice_{t-1} + 0.84 \times LHBEAPrice_{t-1} - 0.01 \times LSZEAPrice_{t-1} - 1.49 \times LTJEAPrice_{t-1} + 0.89 \times LSHEAPrice_{t-1} \quad (10)$$

Equation (10) reveals that Chongqing, Hubei, and Shanghai ETS prices are positively related to Guangdong ETS price, while Beijing, Fujian, Shenzhen, Tianjin ETS are negative related to Guangdong ETS. Guangdong ETS is heavily affected by Chongqing ETS and Tianjin ETS, a 1 % change in Chongqing (Tianjin) ETS increases (decreases) Guangdong ETS by 1.93% (1.49%). Beijing ETS price is inversely related to Guangdong ETS price, while Hubei and Shanghai ETS are positively related to Guangdong ETS. These results are in line with the results from Equation (8). Taken together, the results of cointegration analysis convincingly reveal that the nine ETS market in China are cointegrated. However, the national ETS has not yet enter the long run cointegrating relationships with other regional ETS after a year operation.

1.5.3 Summary

This section carries out the empirical analysis of market co-integration in China from 2014 to 2021. The concept of co-integration among a set of emerging regional carbon markets in China is used to test whether they shared any degree of long-run integration with each other. Not only does this procedure provide a platform for performing detailed static analysis, but it also takes advantage of the restricted VECM model to estimate both short- and long-run relationships' impacts of the emission allowances prices from China's ETS prices.

The evidence of co-integration at rank one (for dataset 1), and rank three (for dataset 2) reveals that ETS markets in China are not mutually exclusive of each other, and that market integration is feasible. Based on the empirical results above, some main conclusions are obtained as follows: First, the analysis for five regional ETS from 2014 to 2019 shows that Beijing, Shanghai, Guangdong, Shenzhen, and Hubei are cointegrated at rank one. In their long-run relationship, the rather large coefficients, 0.450% (0.877%) for Shanghai (Hubei), appear reasonable because they suggest that Guangdong is heavily influenced by the larger market (Hubei and Shanghai ETS). In the short run, the parameters in the VECM suggest that any deviation from the equilibrium co-integrating relationships is mainly caused by changes within the Guangdong ETS. However, the Guangdong ETS remains unaffected by short-term channels from other markets. The lagged prices in the Beijing ETS and Hubei ETS have impacts on their current emission allowances prices.

Secondly, the analysis for nine ETS from July 2021 to July 2022 is examined to have rank three cointegrating relationship, which means the markets are more integrated than the period of 2014-2019. This more favorable result could be attributable to the analysis's use of the most recent data sample (2021-2022) and the inclusion of a more ETS markets. However, the national ETS has not yet enter the long run cointegrating relationships with other regional ETS after a year operation.

1.6 Conclusion

This paper presents a comparative exposition of how the dynamics of regional carbon markets and national markets are propagated and whether these linkage patterns change in response to the movements of a more established market. The paper obtained the daily settlement price of emission allowances spot products from nine ETS - Beijing, Chongqing, Fujian, Guangdong, Hubei, Shanghai, Shenzhen, Tianjin, and national ETS in China. After considering the availability and quality of the daily price data in each ETS, I used two data sets to proceed. The first dataset includes monthly price data from the five largest ETS markets—Beijing, Guangdong, Hubei, Shanghai, and Shenzhen ETS, ranging from 28 April to 25 December. The second datasets cover all ETS - Beijing, Chongqing, Fujian, Guangdong, Hubei, Shanghai, Shenzhen, Tianjin, and national ETS in China, between 16 July 2021 and 15 July 2022. The shorter horizon of dataset 2 is mainly due to the national ETS becoming operation only on 16 July 2021. The integration level of China's carbon prices is examined by testing the relationship of five major regional market monthly prices from 2014 to 2019 and the dynamics of nine ETS using daily prices from July 2021 to July 2022. At this stage in the construction of a national ETS, this study proposes several policy recommendations:

First, eight regional ETS pilots entered the long-run relation, and it seems that the regional ETS are moving towards a more integrated system in the recent period. On the policy level, cointegration indicates that efforts to integrate regional ETS markets better are possible and desirable from an economic efficiency viewpoint.

Second, Hubei and Shanghai ETS prices are tested positively related to Guangdong ETS prices in the long run. One implication for investors is that there is less long-run diversification benefit from investing in these three ETS.

Third, there is long run cointegration found in China's nine ETS pilots. However, the National ETS has been excluded in the long-run relation. This might be because the national ETS currently only regulates the power sector, and no auctions have been placed at the emission allowance allocation mechanism. Limited roles of national ETS in the covering sector induced difficulties in linking the regional ETS to the National one. The government should take more actions to boost the development of the national ETS. For example, it should implement legislative support and include other heavy-emitting industries in the national emission trading. The absence of supportive legislation for China's ETS would result in less interest in compliance among high-carbon-emitting firms and delays in connecting systems.

Moreover, with the increasing need to integrate regional carbon markets, linking multiple regional ETS to form a larger and more prominent 'regional market' has become one of the policy options for further integration. The pilots could be linked bilaterally, unilaterally, or indirectly through the common acceptance of some carbon offset standards. Learning from EU ETS, the government can consider including more sectors, such as heating, cement, manufacturing, public transport, and domestic aviation, in the national ETS. And future goal is to consider linking the domestic ETSs to the international unit to prevent global carbon leakage.

Since opening-up of its economy in 1979, China first established four special economic zones to start a market-oriented economic reform, build a pricing system for a market economy with socialist characteristics. Since then, China has developed seven special economic zones and succeeded in economic development. Learning from the reform plan of the 1970s, the transition from regional ETSs to a single national ETS fits in with China’s economic and social conditions. The differences among the regional pilot carbon markets becomes a source of gaining insights for improving the market design. Notwithstanding, China's national ETS is in its initial phase, and the trading includes only the power sector. The regional ETS pilots continue to play a vital role since other non-power, but heavy-emitting industries are currently trading on regional ETS.

It should be noted that there is some further work to do on this topic. For instance, it is possible that the long-run relationship among the variables changes due to regulatory change.

Econometric technique such as time-varying cointegration or VEC models could be applied when more data are available. In addition, the powerful artificial intelligence models that capture the nonlinear, complicated relationship among regulation rules and the factors regarding ETS can be considered in future research. More broadly, the literature has devoted relatively little attention to the environmental justice aspect of carbon pricing. There has been growing concern over equity aspects versus efficiency considerations.

Chapter 2

Is the Global Carbon Market Integrated?

Return and Volatility Connectedness in ETS Systems

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2. Is the Global Carbon Market Integrated? Return and Volatility Connectedness in ETS Systems

Summary

The Emission Trading Scheme is one of the most important policy instruments to meet global net-zero CO2 emissions target. It is gaining momentum with its increasing market size and constantly improving information mechanisms. With carbon assets becoming prominent as an alternative asset class, the ETS market has engaged a broad range of participants, including not only emissions-intensive energy corporations but also individual and institutional investors. As arbitrage opportunities arise, price fluctuations are likely to occur, which typically have a mutual spillover effect. This paper examines how market fluctuations in these carbon markets interact with each other across four jurisdictions – European Union, New Zealand, California, and Hubei (China). We study return and volatility data, covering the period April 2014 - December 2021, relying on the Time-Varying Parameters Vector Autoregressive model to appreciate the markets' connectedness. We find that the dynamics of carbon markets is mainly explained by itself and not due to spillovers from other markets, indicating that the global carbon prices are largely dependent on themselves. Global negotiations and carbon market events have only a minor impact on the level of connectedness, in contrast to energy or financial crises and the Covid-19 outbreak. We also establish that market size is an important shock absorber.

2.1 Introduction

The Paris Agreement's objective is to keep global warming to 1.5 degrees Celsius above pre-industrial levels (UNFCCC, 2018). However, the United Nation Environment Project (2020) states that the world is heading for a temperature rise in excess of 3°C by the end of this century. To reduce this gap, numerous major energy consumers and CO_2 emitters announced to commit to reaching carbon neutrality by the mid-21st century (Broadstock et al., 2021; National Development and Reform Commission, 2020). Furthermore, many public and private sector organizations have committed to purchase electricity from renewable sources, adopt cleaner technologies, improve efficiency, and conserve water and other resources. However, they often need to supplement those efforts by purchasing carbon offsets or allowances(Kreibich and Hermwille, 2021).

An Emissions Trading System (ETS) is one of the most important instruments through which policy makers hope to achieve their objectives. Emitters of greenhouse gases (GHGs) can choose to either reduce their emissions by adopting cleaner technologies or by buying emission allowances, i.e., paying for their GHG emissions. An ETS incentivizes climate action by allowing entities to exchange emission allowances created by the reduction or removal of greenhouse gases from the atmosphere, such as through switching from fossil fuels to renewable energy or by increasing or conserving carbon stocks in ecosystems such as afforestation (Kreibich and Hermwille, 2021). Emission trading is gaining momentum with its increasing market size and constantly improving information transmission mechanisms (International Carbon Association Partnership, 2022). With these 'carbon assets' becoming prominent as an alternative asset class in investment portfolios, the ETS market has engaged a broad range of participants, including not only emissions-intensive energy corporations but also investors. In 2022, there were 25 regional ETS in operation, 9 under development, and 12 under consideration internationally (International Carbon Association Partnership, 2022). Trades between these developing and developed emission markets increase their ties. However, the enterprises in specific markets may have to bear a cost caused by non-local shocks, namely, spillover effects (Guo and Feng, 2021). As arbitrage opportunities arise, price fluctuations are likely to occur, which typically transgress to other markets (Liu and Gong, 2020).

The EU ETS, California Cap and Trade (CA CaT), and China's ETS are the world's three largest ETS systems (Hernandez-Cortes and Meng, 2020; Ibikunle et al., 2016a; International Carbon Association Partnership, 2022; Nogrady, 2021). New Zealand's ETS (NZ ETS) is unique in that it once permitted unrestricted use of Kyoto credits, exposing it to global carbon price fluctuations where the other ETSs predominantly relate to the 'local' emissions. These four markets are used for the analysis of global carbon market integration in this study. Existing studies paid limited attention to the connectedness of cross-border carbon markets. Hence, it is worth exploring whether there are spillover effects, which make the prices of international carbon markets co-move. If these effects exist, it is relevant to establish which market is driving the others. This paper examines the carbon price interactions and its dynamic drivers among different cross-border ETS[10] markets regarding returns and volatility spillovers. To answer the

[10] It is worth mentioning that other pilot ETS in China, such as Shanghai ETS (started from 2013.11.26), Shenzhen ETS (started from 2013.06.18), and Beijing (started from 2013.12.28) have longer trading history, in 2013 when they started, breakpoints and missing data were observed due to the illiquidity and low trading volume, which impacts the data quality. Furthermore, the Shanghai, Shenzhen, and Beijing ETS are city-wide ETS; we argue that Hubei ETS, as a provincial ETS, is more comparable to the other markets in our study.

above questions, it relies on a time-varying parameter (TVP)-VAR methodology. The sample consists of emission trading systems in four jurisdictions, California, European Union, Hubei (China), and New Zealand, from April 2014 – December 2021. We specifically examine patterns of the total, directional, and net return/volatility spillover effects among these schemes.

We contribute to the literature by including emerging ETSs and studying a more prolonged period. Furthermore, this is the first study to employ the TVP – VAR model with the connectedness approach introduced by (Diebold and Yilmaz, 2012, 2009). It allows for capturing the dynamics of total spillovers as well as the cross-market connectedness. Notably, the reliance on the TVP-VAR overcomes the pitfalls of the standard VAR based connectedness, providing more accurate parameter estimates. This approach helps identify aggregated and directional return and volatility connectedness, which differentiate which ETS markets are net transmitters, and which are net receivers. The approach identifies the main risk triggers of each ETS in the system, and links to specific market microstructure and mechanism.

The relevance of our study is fivefold: (1) Given that return and volatility spillover effects are considered as key characteristics of market integration (Ciarreta and Zarraga, 2015; Han et al., 2020), analysing these is necessary for assessing the efficiency of market linkages. (2) Understanding the return and volatility spillovers between the markets enables investors to manage risk more effectively and make better informed asset allocation decisions. (3) Examining dynamic volatility interconnection among carbon markets is a prerequisite for relating volatility connectedness to specific market characteristics, events, and policies. (4) This paper studies a longer period and allows for analysing the impact of Covid-19. (5) This study provides critical information for investors who are concerned about periods of significant volatility in carbon prices and their transmission across different carbon markets; these findings are of great significance to different stakeholders and provide practical suggestions.

The remainder of the paper is organized as follows: Section 2.2 reviews the relevant literature. Section 2.3 presents the methodology to estimate the return and volatility spillover effects among different regional ETS. Section 2.4 describes the data and sample period. Section 2.5 discusses the empirical results. Section 2.6 concludes and provides policy implications.

2.2 Background

An ETS addresses the heterogeneity in marginal abatement costs of individual firms and plants, and provides the possibility of connecting national schemes (Flachsland et al., 2009; Stern, 2007). A long-term goal for developing an ETS is to initiate an integrated market with comparable pricing across jurisdictions (International Carbon Association Partnership, 2020). Potential benefits for market integration are likely to be substantial, including the support of international cooperation on climate change and the ability to better absorb price shocks (Carbone et al., 2009; Flachsland et al., 2009; International Carbon Association Partnership, 2020; Kachi et al., 2015). Previous studies have a strong preference for linking regional emission-trading systems around the world (Doda et al., 2019; Heitzig and Kornek, 2018; Helm and Pichler, 2015; Holtsmark and Midttømme, 2021; Ranson and Stavins, 2016).

The world's first cap-and-trade systems were introduced in the US[11] to curb air emissions (Borghesi and Montini, 2016; Schmalensee and Stavins, 2017). The EU built its own ETS in 2005[12]. The EU ETS has become the world's first international ETS, covering 31 countries and 11,500 installations and is considered as the prototype system for other ETSs (Borghesi and Montini, 2016). California's cap-and-trade system has been operational since 2013 and has gradually expanded to regulate about 85% of the state's total emissions. It expresses interest in linking its cap-and-trade system with those in other sub-national and national jurisdictions (California Environmental Protection Agency, 2013). New Zealand's (NZ) ETS, launched in 2008, has a distinctive profile due to an economy dominated by the agriculture sector, responsible for almost 50% of New Zealand's GHG emissions. NZ ETS used to be bilaterally linked to other international ETS, meaning that the Kyoto units can be used for compliance in NZ ETS. However, after several changes of domestic market regulation[13], NZ ETS was withdrawn from the Kyoto protocol in December 2013. As a young startup, the China's ETS developed at a fast pace. With nine regional ETS pilots running parallel to a national ETS, the Chinese system is surpassing the EU ETS in market size[14]. The aforementioned ETSs either allow cross-market linkage or the use of external offset credit for compliance, hence induced

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[11] Following Clean Air Act amendments of 1990, the Sulphur dioxide allowance trading Programme was built in the US.

[12] Directive 2003/87/EC. Establishing a scheme for Greenhouse gas emission allowance trading within the community and amending council Directive 96/61/EC. https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX%3A32003L0087.

[13] From mid-2011, as the international price for carbon fell below domestic NZU prices, the unlimited ability to import offsets to NZ ETS has dragged down the price of emission allowances in NZ ETS, leading to a glut of imported international units for surrender for obligations. Thus, from January 2012 onwards, the government gradually introduced bans on various international carbon credit to strengthen the credibility of the NZ ETS, but ended up withdrawing from the second commitment period (CP2) of the Kyoto protocol in December 2013 (Diaz-Rainey and Tulloch, 2018b)

[14] The nationwide Chinese ETS covers 4500 MtCO2e, while the EU ETS covers 1597 MtCO2e (International Carbon Association Partnership, 2022).

potential risk transmission (Gavard et al., 2016). ETS markets have gradually developed into a significant component of the global financial system and provide it with investable carbon assets (Lovcha et al., 2022; Yu et al., 2022). The relationship between emerging and mature carbon markets is crucial for global environmental market integration and liberalization (Guo and Feng, 2021).

With respect to the empirical investigation of spillover effects among ETS, previous studies have examined the price, return, and volatility dynamics between in different markets. For example, carbon price dynamics between identical instruments trading on different exchanges (Benz and Hengelbrock, 2008; Mazza and Petitjean, 2015), carbon spot and future prices on the same exchange (Arouri et al., 2012; Liu et al., 2021),and EUA and CERs[15] price integration (Mansanet Bataller et al., 2010; Nazifi, 2013, 2010; Sadefo Kamdem et al., 2016). In addition, much of research up to now has studied the relationship between ETS and other macroeconomic variables or energy markets (see among others, (Chang et al., 2018; Tan et al., 2020; Wang and Guo, 2018). For example, Benz and Hengelbrock (2008) compare the EUA future contract price across ECX and NordPool from 2005 to 2007. Mazza and Petitjean (2015) study on European Union Allowance (EUA) futures traded on three platforms European Climate Exchange (ECX), NASDAQ OMX, and European Energy Exchange (EEX) — during Phase II of EU ETS (2008-2012). Nazifi (2010) applies the generalized impulse response analysis to investigate dynamic interactions between EUA prices and CER prices during this period.

The introduction of carbon futures markets has resulted in the emergence of a new class of investors who want to have financial exposure to greenhouse gases (emissions)(Arouri et al., 2012; Liu et al., 2021). There is rising interest in the risk management of carbon assets, which can be utilized for a variety of investment objectives, including portfolio diversification, arbitrage, hedging, and speculation (Arouri et al., 2012; Conrad et al., 2012; Schultz and Swieringa, 2014). Liu et al. (2021) study the mean and volatility spillovers by non-linear methods of Granger Causality, showing there is a bidirectional spillover effect between EUA spot and future prices for Phase II and III of the EU ETS. Arouri et al. (2012) suggest that shocks to EUA spot markets have a greater influence on both spot and future market returns than shocks to the futures market. The literature pays limited attention to the connectedness across major ETS systems around the world. Mizrach (2012) finds that prices across exchanges in Europe are cointegrated, and the U.S. carbon market is Granger causing the EU market. Wang

[15] CERs stands for Certified Emission Reductions, which is the carbon product in CDM market.

et al. (2021) investigates the time-varying correlation and long-run price cointegration between the EUA price and Beijing ETS pilot in China, with the use of 61 (for EUA) and 76 (for Beijing) monthly data, from 2013 to 2020. However, this analysis does refrain from price relationship between EUA and other Chinese ETSs and from the directional return and volatility connectedness.

Most of the above studies adopt time-series econometrics (cointegration tests, Granger causality, vector autoregressive models, error correction models, and/or multivariate GARCH models) to examine spillover effects among carbon markets (Diaz-Rainey and Tulloch, 2018b; Lyu, 2021; Mizrach, 2012c; Nazifi, 2010). However, standard vector autoregressive models are estimated with fixed parameters, whereas the GARCH models impose parameter restrictions that are often violated by the estimated coefficients; this makes it difficult to interpret whether shocks to conditional variance persist or not (Nelson, 1991). Furthermore, the directional and time-varying characteristics of spillovers need to be accounted for (Diebold and Yılmaz, 2014). The effects of energy efficiency, improving carbon market efficiency, and the realization of increasing scarcity of natural resources could lead to changing relationships between the key variables. Therefore, we aim to improve the standard VAR model which assumes a static structural relationship over time, while neglecting shifting supply and demand dynamics, growing markets for emission permits, and changes in climate policies.

Diebold and Yilmaz (Diebold and Yilmaz, 2009, 2012) establish a connectedness framework for analysing both idiosyncratic and extrinsic effects based on the estimation of the forecast error variance decompositions (FEVD) from a VAR model. This approach has been applied to spillovers in electricity markets (Do et al., 2020; Han et al., 2020; Ma et al., 2022), crude oil markets (Liu and Gong, 2020), gas market volatility (Broadstock et al., 2020), and energy company stock returns and volatility (Geng et al., 2021a, 2021b; Wu et al., 2021). Recently, scholars have developed TVP-VARs (see, among many others, Cogley and Sargent, 2005; Nakajima, 2011; Primiceri, 2005). In this regard, Antonakakis et al. (2020) propose a dynamic connectedness approach based on TVP-VAR, which allows the variance-covariance matrix to vary via a Kalman filter estimation with forgetting facto[16]. This TVP-VAR-based connectedness approach has the following advantages: (i) it is insensitive to outliers due to the underlying

[16] Kalman filter approaches are fast because state space models encapsulate the Markov property and reduce to a set of recursions [54–6]. The main purpose of our study is to empirically examine the interdependency among global carbon markets; the detailed algorithm of the TVP-VAR model with the use of Kalman filter and forgetting factors can be found in Koop and Korobilis (Koop and Korobilis, 2013).

Kalman filter, (ii) there is no need to arbitrarily choose the rolling-window size, (iii) no loss of observations, and (iv) it can be used for low frequency datasets (Antonakakis et al., 2020; Koop and Korobilis, 2013). The TVP-VAR approaches have been used in related cross-border or cross-region commodity markets (Umar et al., 2021), stock markets (Bouri et al., 2022) , cryptocurrency markets (Asl et al., 2021), and energy markets (Akyildirim et al., 2022; Evrim Mandacı et al., 2020; Li et al., 2010).

This study elaborates on this literature as the aim is to provide a more flexible framework to analyze the time-variation in carbon markets. The next two sections detail the research design.

2.3 Methodology

2.3.1 Overview

The TVP-VARs are state space models for which statistical methods based on the Kalman filter are available. To describe the dynamics of volatility spillovers, the baseline TVP-VAR model is as follows:

$$y_t = Z_{t-1}A_t + \epsilon_t, \quad \epsilon_t|\Omega_{t-1} \sim N(0, \Sigma_t), \quad (1)$$

$$vec(\mathrm{A}_t) = vec(\mathrm{A}_{t-1}) + \xi_t, \; \xi_t|\Omega_{t-1} \sim N(0, \Xi_t), \quad (2)$$

$$\text{where } Z_{t-1} = \begin{pmatrix} y_{t-1} \\ y_{t-2} \\ \vdots \\ y_{t-p} \end{pmatrix}, \text{and } A_t = \begin{pmatrix} A_{1t} \\ A_{2t} \\ \vdots \\ A_{pt} \end{pmatrix}.$$

In the models, p is the lag order, t is the sample length of the model, and $t = p + 1, p + 2, \dots, T$. Ω_{t-1} represents all information available until $T = t - 1$. y_t is an $N \times 1$ vector containing observations on N time series variables. Z_{t-1} represents $N \times p$ matrix. A_t are $N \times Np$ dimensional coefficient matrices while A_{it} are $N \times N$ matrices. ϵ_t and Σ_t are $N \times 1$ and $N \times N$ matrix, respectively. In Equation (2), $vec(\mathrm{A}_t)$ is the vectorisation of A_t which is an $N \times Np$ dimensional vector. The ξ_t is an $\mathrm{N}^2 p \times 1$ dimensional vector. Moreover, Ξ_t are $\mathrm{N}^2 p \times \mathrm{N}^2 p$ time-varying variance-covariance matrices; ϵ_t and ξ_s are independent of one another for all *s* and *t*. The Equation (2), which models the evolution of A_t can be interpreted as a hierarchical prior for A_t.

2.3.2 Estimation of TVP-VAR using forgetting factors

To estimate the above TVP-VAR model, this study uses the Primiceri (2005) and Del Negro and Primiceri (2015) prior, following Antonakakis et al. (2020). The mean and the variance of A_0 are chosen to be the OLS point estimates ($\hat{A}_{OLS}$) and its variance Σ_{OLS}^{A} in a time invariant VAR. Thus, the $\hat{A}_{OLS}$, Σ_{OLS}^{A}, and Σ_{OLS} are equal to the VAR estimation results of the initial subsample (first year): $A_0 \sim \mathrm{N}(\hat{A}_{OLS}, \Sigma_{OLS}^{A})$, and $\Sigma_0 = \Sigma_{OLS}$. Let $y^s = (y_1, \dots y_s)'$ denote observations through time s. In this context filtering refers to inference on A_t through combining of the information contained in a single observation y from the Equation (1) with prior information on A_t expressed through a prior distribution $p(A_t)$. This study considers the benchmark values[17] for forgetting factor, $\lambda = 0.99$ and decay factor, κ=0.96 and keeping them constant at fixed values[18]. Key steps in Kalman filtering are shown in Appendix C.

2.3.3 TVP-VAR-based dynamic connectedness approach

The time-varying coefficients and error covariances are used to estimate the generalized connectedness procedure of Diebold and Yilmaz's spillover index. This procedure is based on generalized impulse response functions (GIRF) and generalized forecast error variance decompositions (GFEVD) first developed by Koop et al. (1996) and Pesaran and Shin (1998). The important step to calculate the GIRF and GFEVD is to transform the VAR to its moving average representation:

$$y_t = \sum_{j=0}^{\infty} \Upsilon_{j,t}\, \epsilon_{t-j}, \quad (3)$$

$$\text{where } \Upsilon_{0,t} = I, \text{ and } \Upsilon_{i,t} = A_{1,t}\Upsilon_{i-1,t} + A_{2,t}\Upsilon_{i-2,t} + \dots + A_{p,t}\Upsilon_{i-p,t}$$

where $\Upsilon_t = [\Upsilon_{1,t}, \Upsilon_{2,t}, \Upsilon_{3,t}, \dots, \Upsilon_{p,t}]'$ and $A_t = [A_{1,t}, A_{2,t}, A_{3,t}, \dots, A_{p,t}]'$. Both the $A_{i,t}$ and $\Upsilon_{i,t}$ are $\mathrm{N} \times \mathrm{N}$ dimensional matrices. The GIRFs represent the responses of all variables j, following a shock in variable i. Let $\Theta_{ij,t}(J)$ denote the J-step-ahead forecast error variances decompositions at time *t*. Each of the elements in the matrix can be obtained by the following formula:

$$\Theta_{j,t}(J) = \frac{\Upsilon_{J,t}\Sigma_t e_j}{\sqrt{\Sigma_{jj,t}}} \frac{\varsigma_{j,t}}{\sqrt{\Sigma_{jj,t}}} = \Sigma_{jj,t}^{-\frac{1}{2}} \Upsilon_{J,t}\Sigma_t e_j, \ \varsigma_{j,t} = \sqrt{\Sigma_{jj,t}}, \quad (4)$$

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[17] For example, for quarterly data, $\lambda = 0.99$ implies observations five years ago receive approximately 80% as much weight as last period's observation (Koop and Korobilis, 2013).

[18] Koop and Korobilis (2013) found that the value added by time-varying decay factors with respect to the forecasting performance was questionable and increased the computation burden of Kalman filter algorithm, thus, we follow Antonakakis et al. (2020) to keep the decay factors constant at fixed values.

where e_j is an $N \times 1$ selection vector with unity in the jth position, and zero otherwise. $\Sigma_{jj,t}$ is the standard deviation of the error term of the *ith* equation, also the *jth* diagonal element in $\Sigma_{u,t}$ (same as Σ_t). The GFEVD represents the pairwise directional connectedness from j to i and illustrates the influence variable j has on variable i in terms of its forecast error variance share. Normalizing each element of the generalized variance decomposition matrix by the row sums as follows:

$$\tilde{\phi}_{ij,t}(J) = \frac{\Sigma_{t=1}^{J-1} \Theta_{ij,t}{}^2}{\Sigma_{j=1}^{N} \Sigma_{t=1}^{J-1} \Theta_{ij,t}{}^2}, \quad (5)$$

with $\Sigma_{j=1}^{N} \tilde{\phi}_{ij,t}(J) = 1$ and $\Sigma_{i,j=1}^{N} \tilde{\phi}_{ij,t}(J) = N$. The denominator represents the cumulative effect of all the shocks, while the numerator illustrates the cumulative effect of a shock in variable i. Using the GFEVD, we construct **the *total connectedness index*** (TCI) by below:

$$C_t(J) = \frac{\Sigma_{\mathrm{i,j=1,i\neq j}}^{N} \tilde{\phi}_{ij,t}(J)}{N} \times 100, \quad (6)$$

This connectedness approach shows how a shock in one variable spills over to other variables. When variable i transmits its shock to all other variables j, this is called ***total directional connectedness to others*** *($C_{i\rightarrow j,t}(J)$)* and it is defined as:

$$C_{i\rightarrow j,t}(J) = \frac{\Sigma_{\mathrm{j=1,i\neq j}}^{N} \tilde{\phi}_{ji,t}(J)}{\Sigma_{\mathrm{j=1}}^{N} \tilde{\phi}_{ji,t}(J)} \times 100, \quad (7)$$

The directional connectedness variable i received from variables j, ***total directional connectedness from others*** ($C_{i\leftarrow j,t}(J)$), can be defined as below:

$$C_{i\leftarrow j,t}(J) = \frac{\Sigma_{\mathrm{j=1,i\neq j}}^{N} \tilde{\phi}_{ij,t}(J)}{\Sigma_{\mathrm{i=1}}^{N} \tilde{\phi}_{ij,t}(J)} \times 100, \quad (8)$$

We subtract ***total directional connectedness to others*** from ***total directional connectedness from others*** to obtain the ***net total directional connectedness*** ($C_{ij,t}$):

$$C_{ij,t} = C_{i\rightarrow j,t}(J) - C_{i\leftarrow j,t}(J), \quad (9)$$

The sign of the net total directional connectedness illustrates whether variable i is driving the network ($C_{i,t} > 0$) or driven by the network ($C_{i,t} < 0$).

2.4 Data

To study the regional carbon markets' co-movement and integration, this paper uses carbon prices from four emission markets — CA CaT, EU ETS, HB ETS, and NZ ETS. After examining several alternative data sources[19], we concluded Thomson Reuters, Wind Database, and Bloomberg provide the carbon prices for the four ETSs with the longest time periods. The sample period covers the period 30 April 2014 through 1 December 2021. All prices use in this study are quoted in Euro. Table 1 summarizes the main features of the sample ETSs. EU ETS and CA CaT are the largest markets, HB ETS is smallest and has the lowest carbon price.

Table 1. Market architecture – differences among four ETS

	EU ETS	NZ ETS	CA CaT	HB ETS
Start	2005	2008	2012	2014
Cap	1579 $MTCO_2e$	34.5 $MTCO_2e$	307.5 $MTCO_2e$	166 $MTCO_2e$
Market threshold	25 $ktCO_2e$	low	25 $ktCO_2e$	10 $MtCO_2e$
Average price	54.76 Euro	30.91 Euro	20.65 Euro	4.92 Euro
Total revenue	31 billion Euro	1.9 billion Euro	16.78 billion Euro	42 million Euro
Covered emissions	39%	49%	85%	45%
Entities	9628	2475	500	373
GHGs covered	CO_2, N_2O, PFC_s	$CO_2, CH_4, N_2O, SF_6,$ HFC_s, PFC_s	$CO_2, CH_4, N_2O, SF_6,$ HFC_s, PFC_s, NF_3,other GHG	CO_2

Source: Own elaboration based on information and data from Emission Trading Worldwide: Status Report, by International Carbon Action Partnership, 2022. Note, the market thredhold of NZ ETS is not clear, in the report by International Carbon Action Partnership, it presents as 'low'. Upon our investigation, any company and investors can enter NZ ETS.

This paper uses the spot price of the European emission allowances (EUAs) since EUA contracts are the major carbon product traded under EU ETS (Lutz et al., 2013; Sadefo Kamdem et al., 2016; Wang et al., 2021). NZ ETS trades in emission allowances known as New Zealand Units (NZUs), which can be held and sold by secondary market traders and auctions. The California Carbon Allowances (CCA) product represents a carbon emission equivalent in CA CaT, which is traded on the ICE Futures Exchange, US. Furthermore, we chose the spot price of Hubei emission allowance (HBEA) as a representative of regional carbon price in China instead of other pilot ETS, for these reasons: i) HB ETS regulates emission trading for a province whose economy is heavily based on secondary industries and coal. ii) Hubei's overall energy structure

[19] Daily spot prices for NZU and EUA are sourced through Bloomberg and Reuters. Prices of HBEA are found from Wind Database. Daily prices of California Carbon Allowance that traded on the ICE Future Exchange US and collected from California Carbon Info (https://www.californiacarbon.info/).

reflects China's as a whole country, hence its deemed representative for the entire economy. ii) Along with corporate and institutional investors, HB ETS attracted a substantial number of individual investors to the trading, with individual investors' daily trading volume accounting for over 30% of total turnover. And iii) HB ETS is the largest pilot ETS in China in terms of trading volume, continuity, social capital invested, and incorporated firm participation.

Weekly returns are calculated as the change in log price, from Friday-to-Friday. The continuously compounded returns of four sets are computed as $r_{i,j,t} = (lnP_{i,j} - lnP_{i,j-1})$, for market i, in week t. We use the realized (historical) volatility as proxy of volatility[20]. Three measures[21] have been applied to estimate weekly volatility of carbon price. The main measure is the standard deviation of weekly return over the five-day interval during each week:

$$\widetilde{SD}_t = \sqrt{\frac{\sum_{i=1}^{M}(r_{ij,t}-\bar{r}_t)^2}{M-1}}, \quad (10)$$

where $\widetilde{SD}_t$ measures the market volatility on week t, $r_{i,j,t}$ is the j[th] daily return in week t, for market i; and M is the number of trading days (in most case M=5). The corresponding estimate of the annualized weekly volatility in percentage is $\widehat{SD}_t = 100\sqrt{52}\widetilde{SD}_t$. According to the calculations above, the sample size is 397 observations for each series. The results in Section 5 are generated with the measure in Equation (10)[22].

Figures 1 and 2 plot the weekly return and realized weekly volatility for the four markets during the sample period. These figures show that all ETS, except HB ETS, have high volatility after March 2020 (when Covid-19 hit)[23]. Both the return and volatility in the NZ ETS in 2014 and 2015 are high after the withdrawal from the Kyoto Protocol. The descriptive statistics of the

[20] We obtain daily closing prices for the four markets; high frequency/intraday data are not available for CA CaT and HB ETS. By using the weekly highest, lowest, open, and close prices, we calculated the realized/historical volatility. To be consistent with the frequency of the historical volatility, we use weekly returns.

[21] Garman and Klass (1980) and Parkinson (1980) volatility measures are used as alternative proxies of volatility in the robustness check. Descriptive statistics of three volatilities are shown in Table B1 in Appendix B.

[22] The empirical results based on the Garman and Klass (1980), and Parkinson (1980) volatility can be found in Figure B1 and B2 in Appendix B.

[23] HB ETS had a 40-day lockdown from February 10 to March 20, 2020. Therefore, the movement of HB ETS during this period is not informative.

return and volatility series are in Table 2. Here, panel A shows that the means of all returns are positive, implying rising prices.

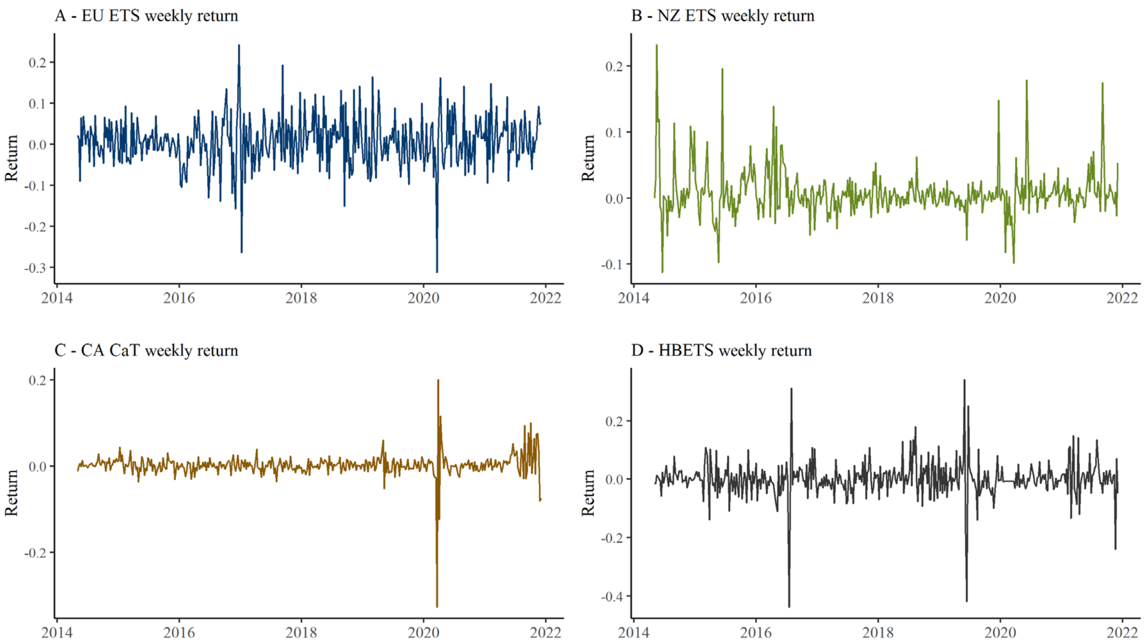
Table 2. Descriptive statistics for the carbon price return and volatility

Panel A: Return							
	Mean	Min	Max	St.dev.	Skew.	Kurt.	ADF
EU ETS	0.007	-0.312	0.243	0.060	-0.312	5.996	-14.37***
NZ ETS	0.008	-0.112	0.232	0.036	1.944	12.041	-10.27***
CA CaT	0.003	-0.326	0.202	0.028	-3.064	59.992	-12.74***
HB ETS	0.001	-0.437	0.342	0.063	-0.764	17.080	-18.74***
Panel B: Volatility							
	Mean	Min	Max	St.dev.	Skew.	Kurt.	ADF
EU ETS	16.734	1.368	78.881	10.081	1.782	8.622	-4.07***
NZ ETS	7.167	0.690	75.503	7.474	4.350	29.793	-5.74***
CA CaT	4.842	0.819	57.247	5.266	5.718	46.145	-4.09***
HB ETS	15.604	0.002	56.364	12.531	1.098	3.557	-5.45***

*Source: Own elaboration based on data from Bloomberg, Reuters, and Wind Database. Note: Sample including carbon prices series from EU ETS, NZ ETS, CA CaT, and HB ETS from April 30,2014 to December 1, 2021. The hypothesis of the Augmented Dicky Fuller (ADF) test is H_0: non-stationary against H_1 : stationary. The lag length is determined by BIC criterion. *** denotes significance at 1% level (Dickey and Fuller, 1979).*

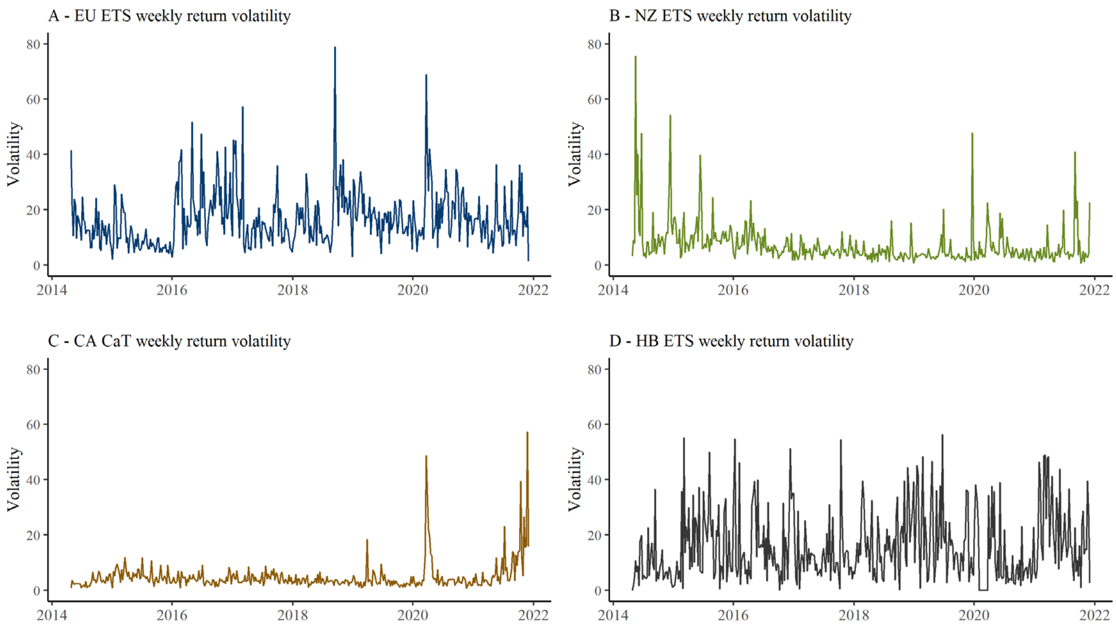
To be specific, prices of EUA, NZU, and CCA rose from 4.34, 1.03, and 11 Euro/ton emission allowances to 76.8, 41.34, and 26.21 Euro/ton, respectively. While the mean return on the HB ETS is positive but close to zero, the price of the HBEA remained rather stable, with the most significant t-statistics from stationarity (ADF) test. Furthermore, several interesting facts emerge in the analysis of volatility (Panel B): 1) The EU ETS has the highest mean, min, and max return volatility of the four series; sharply rising prices and the EU's rapidly shifting carbon reduction policies might be identified as contributors to this high level of volatility. 2) The HB ETS has the second highest volatility. As one of the newly built Chinese pilot markets which started trading in 2014, HB ETS has a flawed market structure, due to the lack of legislation through the provincial legislature in place. Thus high volatility is expected in such emerging market (Zhang, 2015c). 3) CA CaT volatilities increased simultaneously from mid-2021 to end of sample period, indicating a shift in the pattern of spillover effect from or to CA CaT in the post-Covid-19 period.

Figure 1: Weekly return from four ETS



Source: Own elaboration based on data from Bloomberg, Reuters, and Wind Database. Reported are the weekly log-return series, range from 30 April 2014 to 1 December 2021.

Figure 2: Weekly realized (annualized) volatility from four ETS



Source: Own elaboration based on data from Bloomberg, Reuters, and Wind Database. Reported are the weekly volatility series, range from 30 April 2014 to 1 December 2021.

2.5 Results

This section reports the results of empirical analysis by the method presented in Section 3. The results are generated with the first measure[24] (i.e., $\widetilde{SD}_t$, from Equation 10). Section 5.1 presents the total connectedness index (TCI), which measures the influence of one market on all others on average (see Equation 6). Sections 5.2 and 5.3 show the total directional connectedness, which reflects the spillover relationship between one market and all other markets, including total directional connectedness to others ($C_{i\to j,t}(J)$ in Equation 7) and total directional connectedness from others ($C_{i\leftarrow j,t}(J)$ in Equation 8), and net total directional connectedness from others ($C_{ij,t}$ in Equation 9).

2.5.1 Dynamic total connectedness index

In the following empirical model, we use first-order VARs (p=1) (selected by Schwarz information criterion), with 10-step-ahead forecasts[25] (H=10). We define that if this TCI rises, so does network member dependency, and therefore market risk. On the other hand, if TCI decreases the dependence between the members decreases and hence market risk. Table 3 presents the averaged connectedness measures for the markets. The main diagonal of Table 3 shows own-variance shares of shocks, while the off-diagonal elements reflect the interaction across global ETS. The number in the bottom right corner represents TCI of the system. For example, the EU ETS in the return connectedness analysis (see Table 3 Panel A), has received in total of 11.01% shocks from three other markets, 2.88% from NZ ETS, 4.98% from CA CaT, and 3.15% from HB ETS, respectively. On the other hand, EU ETS spilled in total 13.16% to the above three markets: 3.46% to NZ ETS, 5.16% to CA CaT, and 4.54% to HB ETS. The average return (volatility) TCI is 10.42% (12.10%). A total spillover of no more than 10.42% (12.10%) indicates that internal cross-contribution due to individual shocks is not a major driver of future performance across four ETS. Both the dynamics of each of the carbon market are mainly explained by themselves and not due to spillovers from other markets, which indicates that the global carbon prices are largely (albeit not completely) dependent on themselves. In other words, the degree of systemic risk among emission allowance markets is not high.

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[24] The empirical results measured by the other two volatilities can be found in Appendix B (or are available upon request to the authors).

[25] A different choice of forecasting horizon, H from 2 to 9 will be assessed in the robustness check in the Appendix B. Following most of the literature (see for example Yilmaz, 2010), we use 10-step-ahead horizon in the main text.

Our results of carbon market return and volatility TCI are lower than those of the other commodity market TCIs, because we concentrate on carbon markets as such where others connect carbon with other assets. For example, Ji et al. (Q. Ji et al., 2018) concludes 39.47% (30.52) return (volatility) TCI between carbon and energy markets. Tan et al. (2020) find 42.26% (34.82) total return (volatility) TCI. Studies regarding other commodity markets' connectedness conclude 24.58% return connectedness across beverage, fertilizers, food, metals, precious metal, raw materials and oil market (Zhang and Broadstock, 2020), 53.71% among four crude oil markets globally (Liu and Gong, 2020). In the agricultural market connectedness, Umar et al. (2021) reports 18.5% (27.6%) return (volatility) TCI of the dominant agricultural markets.

Table 3. Average connectedness matrix of the system

	EU ETS	NZ ETS	CA CaT	HB ETS	From Others
Panel A: Return connectedness (%)					
EU ETS	88.99	2.88	4.98	3.15	11.01
NZ ETS	3.46	92.03	2.72	1.79	7.97
CA CaT	5.16	2.63	87.59	4.62	12.41
HB ETS	4.54	1.53	4.22	89.70	10.30
To Others	13.16	7.04	11.93	9.57	41.70
Net Total	2.14	-0.93	-0.48	-0.73	TCI=10.42
	EU ETS	NZ ETS	CA CaT	HB ETS	From Others
Panel B: Volatility connectedness (%)					
EU ETS	89.40	2.95	5.71	1.94	10.60
NZ ETS	3.72	86.03	7.36	2.89	13.97
CA CaT	5.36	5.75	84.69	4.21	15.31
HB ETS	2.38	2.51	3.60	91.50	8.50
To Others	11.46	11.21	16.67	9.04	48.38
Net Total	0.86	-2.76	1.36	0.54	TCI=12.10

Source: This spillover table is generated based on 10-step-ahead generalized VAR forecast error variance decomposition. The ij^{th} *entry estimates the fraction of 10-step-ahead error variance in forecasting market i due to exogenous shocks to market j (the spillover from market j to market i:* d_{ij}^{J} *).*

As the objective of this paper is to investigate the behavior of return and volatility spillovers over time, we move beyond the aggregated spillovers for the full sample. We demonstrate the TCI's dynamic evolution over time, which is particularly relevant for examining the TCI's response to major changes in carbon market regulation, economic and energy events, occurrence of extreme weather conditions, and disasters like the Covid-19 pandemic. The dynamic total return and total volatility connectedness are plotted in Figures 3 and 4. It shows that the overall degree of return (volatility) total average connectedness/effects of spillover ranges from 3% (2%)

to 35.74% (35.69%) across the sample period. The literature suggest that the driving factors of the supply and demand in an ETS are: (i) economic growth and government constraints; (ii) international climate change agreements; (iii) regulatory change and arbitrageurs; and (iv) market fundamentals, such as energy prices and weather [42,75-6]. Therefore, we focus on events related to (i) global politics, (ii) carbon market linkage/delinked changes, (iii) temperature and weather, and (iv) public health crises — e.g., Covid-19. Periods with a high degree of connectivity corresponding to the events in Table 4 connect to the event number and are shaded in Figure 3 and 4.

Table 4: Chronology of events for high connectedness

Year	No.	Event	Date	Category
2014	1	G7 Energy Ministers Summit, Rome	2014.05.05	global politics
2015	2	China coal power plant closure	2015.03.01-31	global politics
2015	3	COP21- Paris agreement	2015.11.30-12.12	global politics
2016	4	High-level UN debate on achieving the SDGs + Paris agreement open for signature	2016.04.21-22	global politics
2018	5	COP24	2018.12.2-14	global politics
2019	6	COP25	2019-12.2-13	global politics
2015	7	Korea built ETS	2015.01.01-02.01	carbon market
2015	8	New Zealand delinked	2015.06.01-07.01	carbon market
2019	9	Hubei carbon price spike	2019.05.20-06.03	carbon market
2020	10	Swiss ETS linked to EU ETS	2020.01.01-02.01	carbon market
2021	11	China national ETS operation	2021.07.21-08.21	carbon market
2016	12	Big jump occurred in Global Land-Ocean Temperature Index	2016.02.01-28	weather
2016	13	Worst air pollution episode in China, schools and factories ordered shut, 200 flights cancelled[26]	2016.12.01-30	weather
2017	14	Yangtze River flooding; Hurricanes Harvey, Irma, and Maria	2017.06.30-10.01	weather
2018	15	Multiple deadly heat waves hit East Asia+ Monsoon flood in India where Kerala state reported 500 deaths	2018.07.20-08.30	weather
2014	16	Oil price crisis	2014.06-2015.01	energy
2015	17	Stock market selloff (initially began in China)	2015.06.12-08.26	finance
2018	18	2018 cryptocurrency crash-Bitcoin ultimately fell by approximately 65%	2018.01-02	finance
2019	19	Covid hits China	2019.12.31	covid-19
2021	20	Covid-19 pandemic started	2021.03-2022.12	covid-19

[26] levels of fine particle pollution in Shijiazhuang, capital of northern Hebei province, hit 1,000 micrograms per cubic meter—40 times the WHO standard, in December 2016.

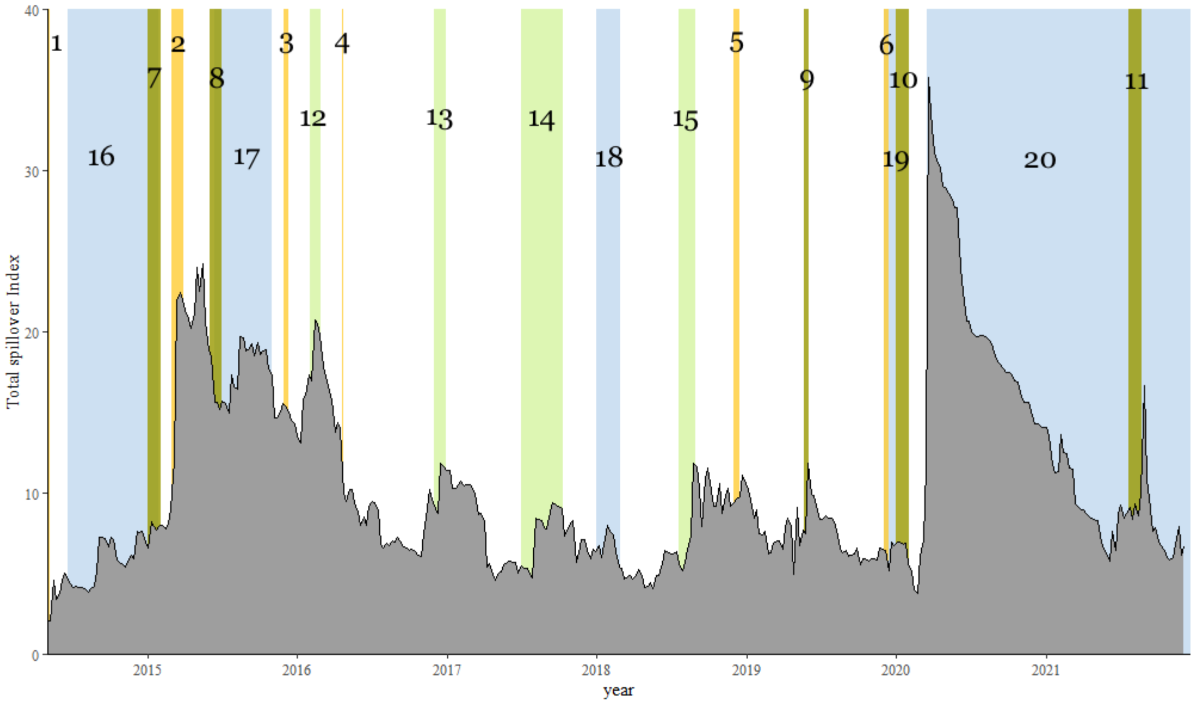
Figure 3 shows that the dynamic connectedness of return network changes considerably over time, especially from 2015 to mid-2016 and following the Covid-19 outbreak, which suggests that the spillovers across carbon markets are time-dependent. The first peak occurred in March 2015 (return spillovers jumped instantly, rising from 9.07% to 21.88%), when the Chinese government shut down the last coal-fired power facilities in inner Beijing as part of a national trend to shut down over 2,000 coal-fired power facilities by 2015 (Event 2). Coal power plants were the most important participants in Hubei carbon markets. Changes in TCI indicate that phasing them out impacts China's carbon markets, which, in turn, affects international carbon markets, given China's dominant role in global carbon emissions. The second peak is associated with Event 17, the global stock market selloff in the second half of 2015. Notably, the stock market crashes initially began in China, resulting in abnormal fluctuations in the world's economies. The return TCI went up to the second peak and remained at around 19%. The third peak of return TCI occurs along with Event 12, when the Global Land-Ocean Temperature Index surged from January to February 2016[27]. Fourth, and highest, connectedness is associated with the Covid-19 outburst and sparking fears of the lockdown policies all over the world (Event 20). During March 2020, the return spillovers jump from 7.09% to 35.74%, and global carbon market spillovers reached their highest so far.

It is worth to notice three moderate intensifications in the return connectedness starting from December 2016, July 2017, and Augustus 2018 respectively, coinciding several extreme weather events (Events 13, 14, and 15). Elevated concerns about global warming and decarbonisation resulted in the TCI to respond. Two other carbon markets events (Events 9 and 11) caused small spikes in the index. In June 2019, the HB ETS experienced a huge price spike, causing volatility in its return series (see Figure 1, Panel D). A reasonable explanation seems that the compliance period of China's pilot ETS is in June, and the price of the Hubei carbon market surged due to unusual activity of participant enterprises trading for compliance before the end of the compliance year. This unusual movement led to spikes in both return and volatility TCIs. Moreover, China launched its national ETS in July 2021, taking 34 power entities away from Hubei ETS at its opening, which caused a loss in allowances demand, and a decrease in the trading volume of emission allowances in Hubei ETS. The results were not surprising in a sense that the national ETS has a higher priority since launched, its existence will inevitably reduce the size, as well as reduce the liquidity of pilot ETS and weaken its influence. Carbon market

[27] NASA recorded that the average global surface temperature in February 2016 was 1.35C warmer than the average for the month between 1951-1980. Sourced by NASA, retrieved from https://data.giss.nasa.gov/gistemp/.

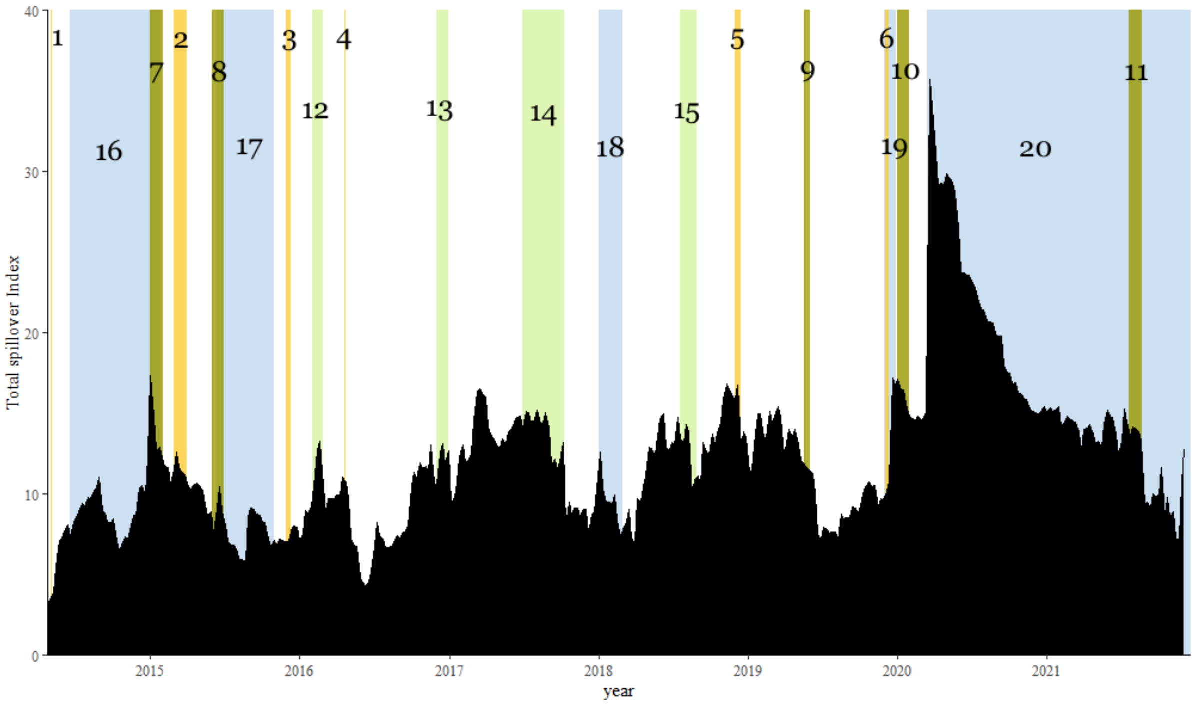
regulation changes might alter investment decisions, resulting in market return changes. For instance, the decreased market threshold incentivizes investors to participate in carbon trading.

Figure 3: Dynamic total return connectedness



Note: Figure 3 plots the dynamics of spillover index (measured by TCI). Y axis shows our sample period, from 2014 – 2021. X axis shows the TCI in the network (numbers in x axis are percentage). Shaded areas with numbers refer to Table 4 above.

Figure 4: Dynamic total volatility connectedness



Note: Figure 4 plots the dynamics of spillover index (measured by TCI). Y axis shows our sample period, from 2014 – 2021. X axis shows the TCI in the network (numbers in x axis are percentage). Shaded areas with numbers refer to Table 4 above.

Figure 4 shows the volatility TCI. There is a slight upward moves in volatility total connectedness from the September 2014 to January 2015 period reflects the effects of continued crude oil price crises(2014-2016). We observe that the first peak (TCI=17.31%) of carbon market volatility connectedness index occurred at the troughs ($44.08 a barrel in January 2015) of the crude oil price (Event 16). The dependence between the markets increases with the decreasing petroleum prices, from September 2014 to January 2015, which in turn results in lower market risk in the carbon market volatility network. Akyildirim et al. (2022)'s analysis of global energy market connectedness index also shows an increase from October 2014 to January 2015, which suggests that the carbon and energy market connectedness indices share the same features during global oil price crisis. During 2016 and 2020, the volatility spillover index moves up and down. The fluctuation of carbon market volatility the spillover index can be the joint consequences of extreme weather events in which booming the awareness of global warming (Event 12 - 15), cryptocurrency crash (Event 18), and uncertainty brought about by Covid-19 in China (Event 19). Noticeably, an instant upward moves from 9.66% to 17.15% is witnessed following COP 25 (Event 6), however in December 2019 when Switzerland quit the EU ETS and Covid-19 first hit China, the index fall again (European Commission, 2019). In March 2020, an extraordinary shift occurred when the Covid-19 virus began spreading globally: volatility TCI rose from 14.55% to 35.69%. Following the Covid-19 outbreak (Event 20), the total risk in the ETS markets, as measured by the TCI level, reached historic highs owing to the quick and furious reaction to growing uncertainty at both the individual and national level. The unprecedented increase in the TCI as a result of the Covid outbreak is supported by other studies in energy markets (Akyildirim et al., 2022; Bouri et al., 2021; Tiwari et al., 2022).

Our findings suggest that global negotiations and other political issues (e.g., Events 1, 3, 4, and 5) and carbon market events (Event 7 -11) have only a minor impact on the level of connectedness. Their impacts are far less than that of the energy or financial crises, and Covid-19 outbreak. In particular, the return spillover index (TCI) is less influenced by the global crude oil crises during mid-2014 and early 2015, but more so by financial market crashes and extreme weather events (e.g., Event 12-15). The volatility spillovers, on the other hand, seem mostly impacted by the crude oil crisis and cryptocurrency crash (Event 16, 18). Both return and volatility spillovers are heavily impacted by the Covid-19 outburst, which resulted in increasing market risk across the carbon market network.

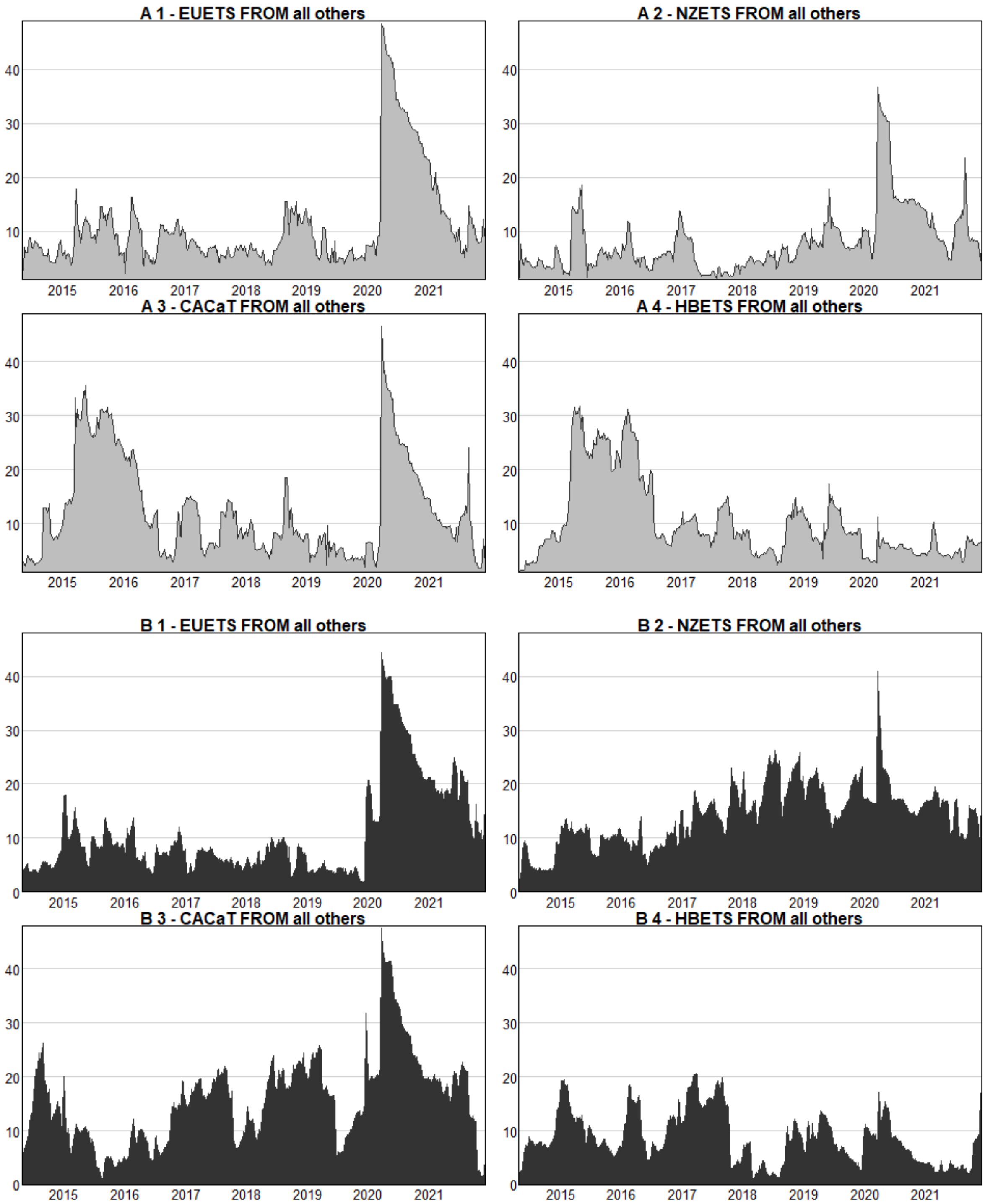
2.5.2 Connectedness for 'From' and 'To'

In this section, we investigate dynamic spillovers and their directions for each of the ETSs. Recall that the diagonal of Table 3 represents the shocks from each of the markets themselves, while the upper and lower part of the off diagonal show the spillovers across the markets. The highest value of the (aggregated) return spillovers from others are for CA CaT ($\Sigma_{j\neq 3} d_{3j}^{J}$=12.41%), and the lowest value of the (aggregated) return spillovers from others are for NZ ETS ($\Sigma_{j\neq 2} d_{2j}^{J}$ =7.97%). In terms of the (aggregated) return spillovers to others, EU ETS and NZ ETS remain the highest ($\Sigma_{i\neq 1} d_{i1}^{J} = 13.16\%$) and the lowest ($\Sigma_{i\neq 2} d_{i2}^{J} = 7.04\%$). The volatility connectedness measures (see Table 3, Panel B) reveals that NZ ETS received 13.96% (aggregated) volatility spillover from other three markets. The highest value of spillovers to other markets are for CA CaT (16.67%), while HB ETS has taken an aggregated average value of 9.04% spillover. All the numbers shown in Table 3 are average aggregated measures.

As we are interested in the conduct of return and volatility spillovers over time, we also plot the directional evolution through time. Figure 5 and Figure 6 respectively show the directional return and the volatility spillovers from and to four ETS over time. The plots in Figure 5, except for HB ETS, reveal that there have been marked increases of spillovers from other markets right after the Covid-19 outbreak, both for the return and volatility networks. Although the average level of connectedness *From Others* remains 7-13 percentage for the markets, the spillovers *From Others* peaked at almost 50% for EU ETS and CA CaT in March 2020It shows that the general pattern of HB ETS regarding return and volatility appear to be unaffected by the Covid-19 outbreak. This is due to the strict lock-down, which shielded the Chinese market temporarily from further shocks. Considering that the Covid-19 policies in China are unique in terms of the strict lockdown, the carbon market movement could not be impacted by the other markets in other countries. Furthermore, there is a slight upward trend shown in return (volatility) systems of NZ ETS since mid-2017 (mid-2016), showing that delinking NZ ETS to global markets has increased the market risks in NZ ETS.

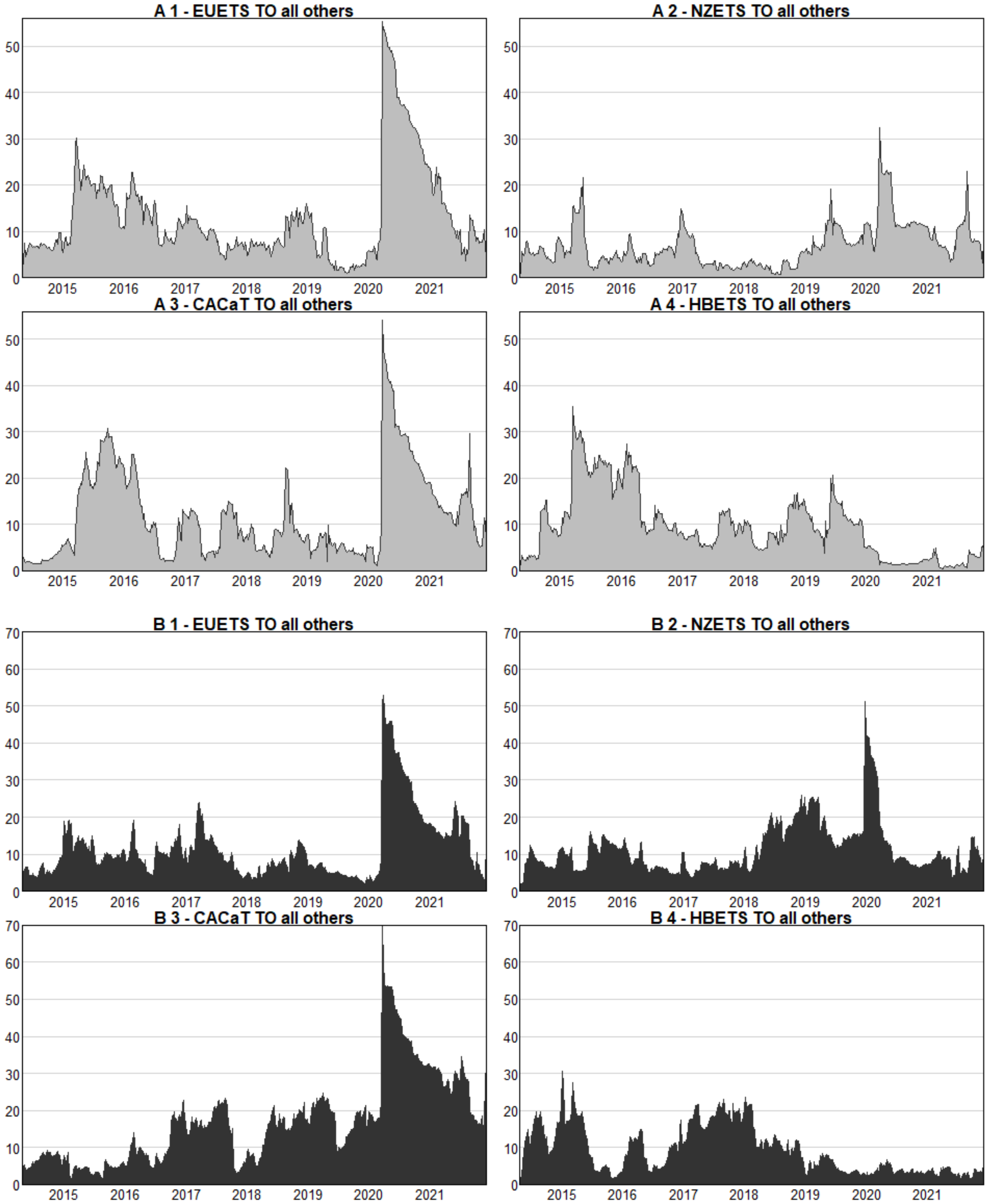
In terms of the directional spillovers from each of the four to all markets, the EU ETS has the largest (aggregated) share of spillovers (13.16%) to all others in the return system while CA CaT has the largest (16.67%) to the others in the volatility system. Since March 2020, the return (volatility) spillovers from EU ETS and CA CaT to all others reached the unprecedented points, 55.30% (50.86%), and 54.04% (69.69%), respectively. There has been a steady decline of return spillovers from HB ETS to the others, from approx. 10% to nearly 2%, since mid-2019.

Figure 5. Dynamic directional return and volatility spillovers - *FROM* four markets



Note: Panel A1 to A4 in grey colour are from the return connectedness system, Panel B1 to B4 in black colour are for the volatility connectedness system. The return series contains 397 observations (each) starting from 2 May 2014 to 1 December 2022 while the volatility series contains 398 observations (each) starting from 25 April to 1 December 2022. The predictive horizon for the underlying variance decomposition is H=10, both are first-ordered VAR (p=1).

Figure 6. Dynamic directional return and volatility spillovers – *TO* four markets



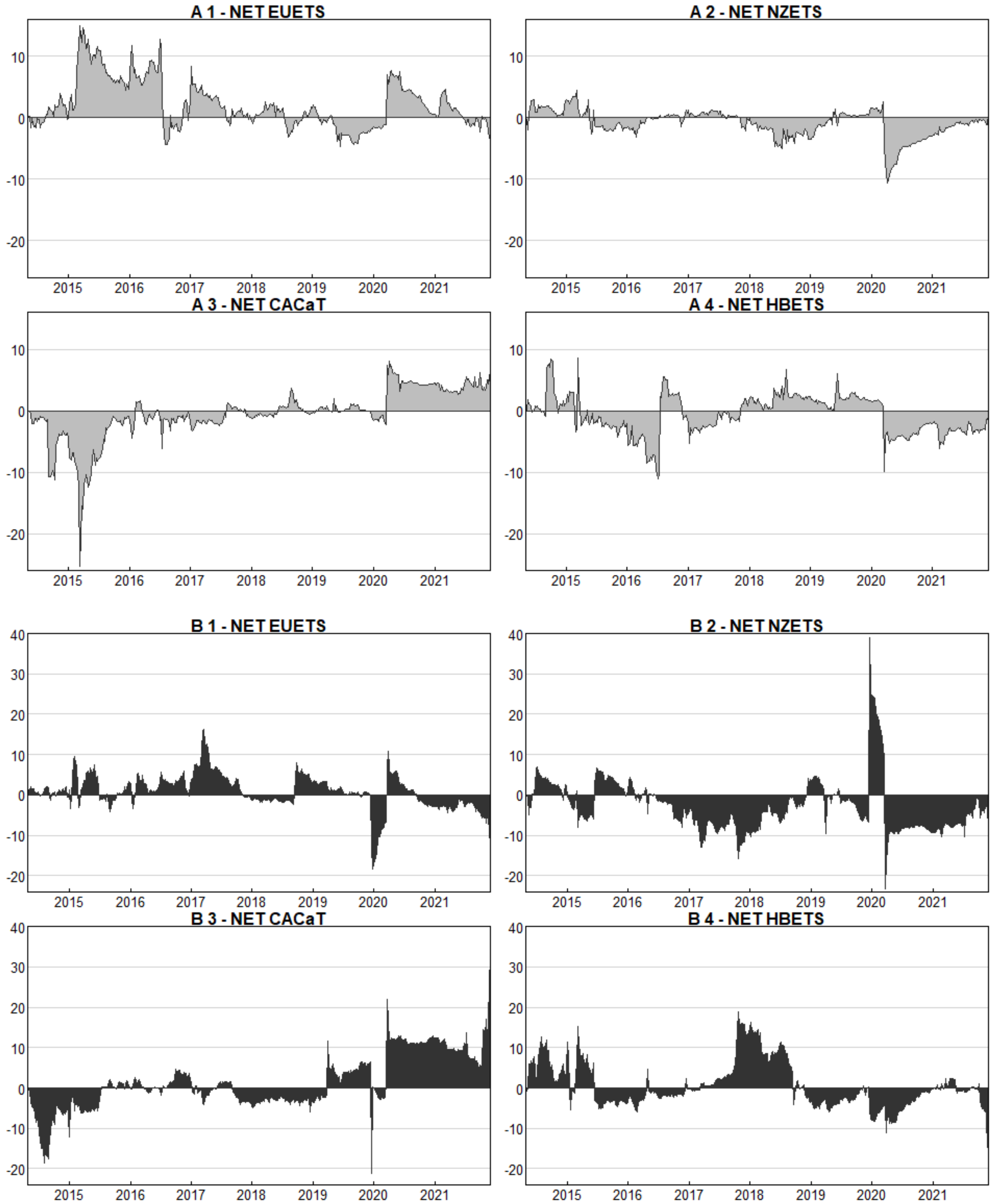
Note: Panel A1 to A4 in grey colour are from the return connectedness system, Panel B1 to B4 in black colour are for the volatility connectedness system. The return series contains 397 observations (each) starting from 2 May 2014 to 1 December 2022 while the volatility series contains 398 observations (each) starting from 25 April to 1 December 2022. The predictive horizon for the underlying variance decomposition is H=10, both are first-ordered VAR (p=1).

2.5.3 Net total connectedness

Here, we report the results for the four markets net total directional connectedness. This is defined in Equation (9) and calculated by subtracting *total directional connectedness to others (*$C_{i\leftarrow j,t}(J)$*)* from *total directional connectedness from others (*$C_{i\rightarrow j,t}(J)$*)*. Given that a net positive (negative) value in the last row of Table 3 means that the market (from one of the four columns) is a net transmitter (receiver) of the shocks, hence, leading (being led by) the network. Therefore, the results shown in the rows Net Total in panels A and B of Table 3 point at the difference between the transmitting and the receiving shocks of each markets considering the entire network. Table 3 suggests that EU ETS is the largest transmitter (2.14%) while NZ ETS is the largest receiver (-0.93%) in the return connectedness systems. Notably, the EU ETS is the only return spillovers transmitter, confirmed by the positive value shown at the bottom of Table 3 Panel A. In terms of the volatility connectedness system, CA CaT is the largest transmitter (1.35%), followed by EU ETS (0.86%), while NZ ETS is again the largest receiver (-2.76%). NZ ETS has the least and only negative value in the last row – Net Total, which means all other three markets are identified as volatility transmitters, while NZ ETS receives more spillovers from the system than it transmits.

Figure 7 displays the evolution of net return and volatility spillover of the four ETSs. Positive values indicate periods when a specific carbon market acts as a net-transmitter, whilst negative values indicate the period when one of the markets receives, on net terms, from all others. An inspection of Figure 7 leads to the following observations: First is that EU ETS has a persistent net-transmitting role in the return connectedness system. The phenomena could be explained by the maturity of the market performance and the market size (in terms of total participants, price, and revenues) of the EU ETS. Second, in terms of volatility net total spillovers, what stands out in Figure 7, is the spike of 39.5% on 13 December 2019 of the Net total spillovers of NZ ETS. Albeit NZ ETS is a net receiver in the aggregated level, in December 2019 it was leading the network in the short-term. This discovery matches the volatility jumps (from 1.72 to 47.81%) in New Zealand ETS's volatility series (see. Figure 2), where the market volatility was substantially impacted by Covid-19 when it first hit the world. Third, it shows that after the Covid-19 outbreak, the CA CaT became a net transmitter while the NZ ETS and HB ETS remained in their roles as shocks receiver in the carbon trading system.

Figure 7. Net return and volatility spillovers - four markets



Note: Panel A1 to A4 in grey colour are from the return connectedness system, Panel B1 to B4 in black colour are for the volatility connectedness system. The return series contains 397 observations (each) starting from 2 May 2014 to 1 December 2022 while the volatility series contains 398 observations (each) starting from 25 April to 1 December 2022. The predictive horizon for the underlying variance decomposition is H=10, both are first-ordered VAR (p=1).

2.6 Conclusion

ETSs bring together private sector, policy, and decision makers to engage in a clean(er) transition to meet net-zero emissions targets. The financial sector has been particularly active in the development of the carbon market. Understanding the interactions between these markets enables the efficient and effective operation of carbon markets. This paper studies the connectedness among four Emission Trading Schemes: California's Cap-and-Trade (Ca CaT), China's Hubei ETS (HB ETS), the EU ETS, and New Zealand's ETS (NZ ETS), from 2014 to 2021. The sample period covers a wide range of events, for example, stock market crashes, global climate change negotiations, political events, carbon market regulation, and the Covid-19 outburst. Given the effects of increasing energy efficiency and clean technology adoption, improving emission market efficiency, and the organic growth of linkages between ETS systems, the spillover effects among our four markets may be affected during the sample period. The study employs a TVP-VAR methodology to measure the connectedness along the four markets.

We find that the dynamic connectedness of return and volatility networks changes considerably over time, especially during Covid-19 outbreak. This suggests that spillover across carbon markets is a time-dependent phenomenon. We establish that the average return (volatility) total connectedness index (TCI) is 10.42% (12.10%), which indicates that the global carbon prices are largely dependent. Changes in global climate change politics and carbon market reforms appear to have only minor impact on TCI, whereas the occurrence of energy and financial crises have a substantial effect (both regarding return and volatility). The EU ETS has a persistent net-transmitting role, as it is the largest and only transmitter in return connectedness, whereas the CA CaT is the largest transmitter in the volatility connectedness. CA CaT and EU ETS share several common features regarding their resilience: They are both structured upon three compliance phases; their sector coverage is similar, and their market threshold (25 $ktCO_2e$) is substantially higher than that of the other two, which means their participants are larger in scale, hence, less vulnerable to public crisis. NZ ETS is the largest shock receiver in both the return and volatility connectedness systems. HB ETS has hardly been impacted by the Covid-19 outbreak, unlike the other three markets. A potential explanation is that the Covid-19 policies in China are unique in terms of the strict lockdown: due to closing the boarder, the movement at HB ETS could hardly be impacted by other ETSs.

Most studies in the field of carbon markets focus on the relationship between the carbon market and other energy and/or financial markets (Chang et al., 2018; Q. Ji et al., 2018; Tan et al., 2020;

Tiwari et al., 2022). Other studies concentrate on local/domestic carbon markets (Conrad et al., 2012; Diaz-Rainey and Tulloch, 2018b; Lyu, 2021). These previous studies did not deal with the directional return and/or volatility spillovers (from/to a particular market) across the four markets. Our four-dimensional time varying parameter VAR model solves the defects of constant parameters and static analysis of a traditional measurement model.

The results lead to important policy implications. Firstly, investors and portfolio managers may diversify their portfolio risks by investing in carbon market pairings that are unlikely to transfer shocks to one another during anomalous events. Investors should attach special attention to New Zealand and EU's ETS when formulating portfolio strategies since they have been in the role of net receiver and transmitters, respectively in the system; net receivers are vulnerable under market unrest. Secondly, efficient coordination and monitoring mechanisms among cross-country carbon markets shall be put in place during period with higher uncertainty, namely energy crisis period and extreme weather events, to help policymakers to design timely interventions to alleviate the contagion risk in carbon market networks. Thirdly, albeit Hubei ETS has the smallest market size compared to the other three in our study, extreme prices spike in Hubei ETS, and the launch of China's national ETS could increase the market risk transmission in carbon market networks. Hence, a smooth transmission from China's pilot ETS to national pilots is needed in a sense that the carbon market regulation change might alter investment decisions, resulting in market return changes.

As for future work, we envision are several directions for extension. There is a definite need for constructing high frequency data to analyze the connectedness on a daily frequency. Furthermore, it is interesting to include more carbon markets in the panel, for example, the South Korea ETS, which is another nationwide ETS in Asia, Regional Greenhouse Gas Initiative (RGGI) in North America, and UK ETS that quit EU ETS since Brexit.

Chapter 3

Volatility Spillovers in the Interconnected NordPool Electricity Markets – The Effect of Carbon Price

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3. Volatility Spillovers in the Interconnected NordPool Electricity Markets – The Effect of Carbon Price

Summary

Integration of electricity markets remains a cornerstone of the European economic integration. However, the price of electricity in liberalized wholesale electricity markets has become one of the most volatile financial instruments with its dependence on weather and climate-related conditions, the growing share of renewables, and the increasing marginal cost of carbon that the electricity generators are facing, Concerns have ben now raised on the market integration progress especially in highly geographically and economically linked European areas, such as the Nordic region. The Nordic electricity market is believed to be the well-functioning market with a growing amount of renewable energy in the world. Hence, the Nordic market can show some light on wholesale price developments in integrating electricity markets experiencing a growing share of renewable energy. Climate policies, for instance, the European Union emissions trading system (EU ETS), as a well-established carbon market in the EU, will increase electricity price levels in general. Our results show that Sweden is a net volatility spillover transmitter while Denmark bears the most significant shocks from the system.

3.1 Introduction

Electricity is a critical service and infrastructure for national economic development (Cramton, 2017). Due to the non-storable nature of electricity, electricity markets are more complicated to rectify supply and demand imbalances than other commodity markets (Ma et al., 2022; Uribe et al., 2020). With their dependence on the weather and climate related conditions, the growing shares of renewables, and increasing marginal cost of carbon that the electricity generators are facing with, the price of electricity became one of the most volatile financial instruments (Do et al., 2020).

Electricity market integration can reduce idiosyncratic exposure to volatility risk in each market, and therefore limit the probability of energy crises and energy shortages in national or regional markets. The US Energy Policy Act of 1992 promoted the electricity wholesale markets by requiring utilities to open the transmission systems, which has formed a regional network spanning 11 separate spot markets (De Vany and Walls, 1999; Park et al., 2006); since then the price dynamics and integration among 11 US markets has been extensively discussed (see among others, Mjelde and Bessler, 2009). In the same vein, Australia has established the National Electricity Market (NEM) since 1998, made up by five regional markets (Han et al., 2020; Nepal and Foster, 2016). In order to remove barriers between member states and achieve cross-border electricity supply, the European Union electricity market integration have been considered and discussed as early as in 1986 (Do et al., 2020; Jamasb and Pollitt, 2005; Pollitt, 2019), and was put into practice in 1990[28].

The market integration progress has been a crucial issue especially in highly geographically and economically linked areas, for instance, in the Nordic region. The Nordic electricity market - NordPool is believed to be the most wee-functioning market in the world (Amundsen and Bergman, 2006). The generation mix in the Nordic region is heavily dominated by renewables. The electricity derived from renewable production in Denmark, Norway, Finland, and Sweden, has reached 72.4%, 100%, 69.0% and 88.7%, respectively. In spite of these high levels of clean energy penetration, the Nordic region is expected to experience faster growth in renewables in the future decades (Bertrand, 2020; Jan, 2019). Integration of national electricity markets, characterized by a variety of renewable (e.g., wind power in Denmark, hydro power in Norway, and nuclear power in Sweden and Finland) and non-renewable (e.g., fossil fuels in Finland) generation mixes, continues apace. Renewable energy, such as wind power and hydropower, is inherently unstable; due to their dependence on climatic conditions, weather intermittency exacerbates electricity spot price volatility in the absence of feasible electricity storage (Uribe et al., 2020). Investors in NordPool are exposed to the risk of price fluctuations in merchant power prices. One of the most pressing issues to be tackled is the possible changes in the volatility dynamics of wholesale electricity prices. And the Nordic market can shed some light on price fluctuations in future integrated renewable dominant electricity markets.

This paper analyses volatility spillovers across the four Nordic countries and examine how carbon prices influence those spillover effects. The research questions which this study is trying to answer include: what is the volatility connectedness level among the Nordic countries? Whether and how changes in carbon prices drive volatility spillovers in integrated Nordic electricity markets?

[28] Council Directive 90/377/EEC of 29 June 1990 concerning a community procedure to improve the transparency of gas and electricity prices charged to industrial end-users. Retrieved from: https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX:31990L0377.

The Nordic electricity market is mainly formed by four countries – Denmark, Finland, Norway, and Sweden, which includes 13 bidding areas, there are price differences among bidding areas. Price movements in different markets enhance the arbitrage opportunities, the spillover effects appear among markets. Price fluctuation (e.g., volatilities) in the same type of market typically has a mutual spillover effect, which refers to the notion that the volatility of one market can be passed to another. Cross-spillovers between electricity markets facilitate international market risk sharing. In integrated markets, changes in one local electricity market can affect not only local power consumption and wholesale prices, but also the electricity markets of other countries via cross-border trade, as electricity markets aggregated massive amount of interconnected financial transactions. Taking Norway as an example, the wholesale electricity price in Norway is affected by the weather condition, wind generation, hydro output, as well as climate change policies; and shocks are passed on to the Swedish market. As a result, power companies under Swedish power markets may bear the impact caused by non-local shocks, contributed by Norway. Furthermore, the climate policies, for instance, the European Union emissions trading system (EU ETS), as a well-established carbon market of EU, will increase electricity price levels in general (Aatola et al., 2013). The power enterprises are the most active traders in the EU ETS, and thus the interaction between the Nordic wholesale electricity markets and EU ETS is of particular importance.

The novelty of our approach is three folded. First, we use the connectedness approach based on both the time-varying parameter VAR (TVP-VAR, thereafter) and rolling window-based VAR (RW-VAR, thereafter) models to analyse integration in Nordic electricity markets, contributing to the scare literature in the electricity volatility connectedness across four countries (Sweden, Finland, Denmark, Norway). Second, we divided Norwegian market to two prices due to the observed difference between northern and southern electricity prices. Thirdly, we examine how changes in carbon price influence those spillover effects, to the best of our understanding, this is the first study to examine the role of carbon price on volatility spillovers among Nordic electricity markets. Understanding these issues is important for market participants (e.g., electricity producers, retailers, investors, and users) to adopt appropriate risk management strategies to reduce the negative effects of electricity price volatility. It is also important for the regulators of electricity markets to devise appropriate policies to address potential electricity crises and to maintain electricity market stability.

The remainder of the paper is organized as follows: Section 2 reviews the relevant literature. Section 3 presents the methodology to estimate volatility spillover effects among different regional ETS. Section 4 describes the data and sample period. Section 5 discusses the empirical results. Section 6 concludes and provides policy implications.

3.2 Background

Renewable Energy (RE) penetration has been increasing globally in the last ten years (BP, 2022). Advanced economies, e.g., European Union, has generally higher portion of the renewables in the electricity generation, 39% of its gross electricity consumption (International Energy Agency, 2022). However, the source of power generation differs within countries across Europe. European countries, for instance, Italy, Poland, and Netherland are still dominated by fossil fuels, respectively; nuclear power is the main source of French power generation, while the Nordic power generation is largely relied on renewable energy (Eurostat, 2022). The Nordic countries 'deregulated' their power markets by introducing free competition in the early 1990s, bringing their individual markets together into a common large market – Nord Pool (Flatabo et al., 2003; Torstein Bye and Hope, 2005). Since then, the transmission capacity and coupling were in place in the Nordic countries, the European continent, and the Baltics. Hence, the power from different sources both enters the grid, in which ensures a more liquid market. The NordPool is transitioning to a system fully based on sustainable energy resources. Specifically, Denmark, as a leading country in wind energy, has a long tradition of developing and integrating renewable energy to its electricity sector. The electricity derived from renewable energy has reached 72.4% of the electricity supply by the end of 2020, in which the wind energy and biomass contribute around 50% and 21.2%, respectively (Danish Energy Agency, 2021). In Norway, 100% of the electricity production come from low carbon sources, in which 98% come from renewable energy sources, namely, hydropower, wind, and thermal energy (International Energy Agency, 2022; Ministry of Petroleum and Energy, 2016). Sufficient precipitation and inflow to dams and reservoirs are critical due to hydropower's major role in Norwegian electricity production. In Finland and Sweden, the share of low carbon sources in power generation is 69.0% and 88.7%, respectively, while the share of renewable energy is 48.8% and 66.3%. The aforementioned renewable energy, such as wind power, depends on meteorological conditions, and hydropower depends on water volume and elevation change. In the absence of viable electricity storage, the electricity price in renewable-based markets, NordPool, is more volatile (Ketterer, 2014; Kyritsis et al., 2017; Uribe et al., 2020).

The literature on the linkages between electricity markets has been extensively investigated (see, e.g., Amundsen and Bergman, 2006; Bunn and Gianfreda, 2010; De Vany and Walls, 1999; Do et al., 2020; Gugler et al., 2018; Han et al., 2020; Ma et al., 2022; Nepal and Foster, 2016; and Park et al., 2006). Most studies in electricity market integration have focused on European and Australian electricity markets (Bunn and Gianfreda, 2010; Gugler et al., 2018), with the use of daily spot or forward price data. The volatility spillover effect across different electricity markets have been well documented in the literature (see, e.g., Do et al., 2020; Han et al., 2020; Ma et al., 2022; Uribe et al., 2020). Han et al. (2020) studies the volatility spillovers between electricity prices across five regions in Australian National Electricity Market (NEM). They reported the volatility connectedness among Australian NEM as 35.92%, the connectedness is typically more pronounced between physically interconnected markets. In the same vein, Do et al. (2020) investigates the volatility connectedness between the Irish and Great British electricity markets. They reported an around 5% volatility connectedness between two markets over the 2009-2018 sample period. Their results showed that the volatility connectedness is lower than that of the Australian NEM as Han et al. (2020) examined, the low connectedness was argued due to the inefficient flows across the two interconnectors between Britain and the Irish Single Electricity Market (SEM) before October 2018. Hasan et al. (2021) investigates the time-frequency connectedness between Asian electricity sectors. Their results showed geographically connected markets such as China mainland, India, and Hongkong are more connected than that of the geographically distant markets. Table 1 Panel A concludes the relevant literatures in electricity market integration with the use of connectedness method. The above studies generally concluded that physically and economically interconnected markets have larger spillover effects across the systems, hence larger market risks. In such systems, the risk propagates more fluently, allowing for a decrease of idiosyncratic market risks, thus reducing the energy shortages in each of the domestic markets.

Past studies have largely focused on the price mechanism in NordPool (Haugom et al., 2018; Hellström et al., 2012; Sotiriadis et al., 2016; Souhir et al., 2019), the linkage between NordPool electricity price and other energy or emission market prices (Chuliá et al., 2019; Daskalakis and Markellos, 2009; Ma et al., 2022), and electricity spot-forward price relation in NordPool (Botterud et al., 2010; Weron and Zator, 2014). Table 1 Panel B briefly concludes the abovementioned papers in NordPool. Few studies examine the linkages in Nordpool market (Ma et al., 2022; Uribe et al., 2020). NordPool market provides unique opportunity to study the highly integrated market as well as identify the challenges derived from a higher share of electricity from renewable energy generation. Our aim is to fill this gap by analysing cross-spillover between prices in Nordpool interconnected electricity wholesale market that consist of a variety of renewable power sources.

Table 1. Brief literature on electricity market integration and NordPool electricity prices

Panel A: Summary of studies on connectedness in electricity markets				
Reference	Study area	Study period	Model type	Data
Ma et al. (2022)	12 European day-ahead wholesale spot electricity markets	Sep 2009 - Aug 2020	Time-frequency volatility connectedness	Hourly price
Naeem et al. (2022)	Australian National Electricity Market (NEM)	May 2005 - Dec 2020	RW-VAR, time and frequency, and asymmetric connectedness	Daily price
Hasan et al. (2021)	Electricity sector of 10 Asian jurisdictions	Apr 2007 - Aug 2020	RW-VAR connectedness and frequency connectedness (Baruník and Křehlík, 2018)	Daily stock price
Han et al. (2020)	Australian NEM	Jan 2010 - Dec 2017	RW-VAR connectedness	Daily price
Do et al. (2020)	Irish and Great Britain markets	Oct 2009 - Oct 2018	Asymmetric connectedness based on RW-VAR	Half hourly price

Panel B: Summary of studies on Nordpool electricity markets				
Reference	Topic	Study period	Model type	Data
Souhir et al. (2019)	Electricity market variations on the Nordic stock market returns	Jul 2017 - Dec 2017	VaR, c-DCC-FIGARCH, CVaR and ΔCVaR	Hourly spot electricity price
Sotiriadis et al. (2016)	Price and volatility interrelationships in five European electricity markets	Jan 2009- Aug 2012	A novel VAR model, CCC-MGARCH model, DCC-MGARCH	Daily spot electricity price
Chuliá et al. (2019)	Links between energy markets in Europe (including NordPool)	Nov 2008- Jun 2016	RW-VAR	17 forward price covering electricity, gas, coal, and carbon
Daskalakis and Markellos (2009)	Links between emission and electricity markets	Sep 2006- Oct 2007 Mar 2005- May 2007	Regressions	Daily electricity and carbon price

Hellström et al. (2012)	possible causes behind electricity price jumps in the NordPool	Jan 1996-Feb 2006	a mixed GARCH–EARJI jump model	Daily spot electricity price
Weron and Zator (2014)	Relationship between spot and futures prices in NordPool	Jan 1998-Dec 2010	Regression models with GARCH residuals	Weekly price
Botterud et al. (2010)	Spot- and futures prices relationships in NordPool	1996-2006	descriptive statistics and simple regression analysis	Weekly price
Haugom et al. (2018)	Forward premium of futures contracts in the NordPool	Jan 2004-Dec 2013	Regressions	Weekly price
Nomikos and Soldatos (2010)	Major risks (e.g., spike risk, short-term risk) in power prices in NordPool	Jan 1993-Feb 2004	three-factor spike model	Daily system prices

Regarding the methodological frameworks employed in the electricity market integration literature, they range from standard cointegration and Autoregressive Distributed Lag analysis (ARDL) (see, among others, Gugler et al., 2018; Böckers and Heimeshoff, 2014), to time-varying cointegration tests (de Menezes and Houllier, 2016; Nepal and Foster, 2016). Such techniques (e.g., cointegration) have not considered the dynamics of volatility connectedness in electricity markets, which is a necessity for assessing the progress toward higher degrees of wholesale power markets integration.

The connectedness strand of the literature, developed recently by Diebold and Yilmaz (2009, 2012, 2014), is the most relevant for our study (hereafter DY method). The DY method construct the spillover index by the forecast error variance decomposition of the VAR model. The notable feature of DY method is that can describe the direction of spillovers and the dynamics of spillover. Notably, the DY connectedness method overcomes not only the problem of fixed parameters assumed in cointegration tests, but also the drawbacks of multivariate GARCH models in capturing time-varying features of spillover effect (Do et al., 2020; Han et al., 2020; Liu and Gong, 2020; Ma et al., 2022). The DY method has many advantages, but it still has several drawbacks, namely, i) estimation based on a rolling window VAR (hereafter, RW-VAR) induces loss of observations, ii) arbitrary in selecting window size, and iii) loss of observations in first window. Hence, this study first analyse the connectedness in NordPool by DY rolling window VAR, then extend the model to a time-varying parameter VAR (TVP-VAR), followed by (Antonakakis et al., 2020). The TVP-VAR-based connectedness approach has the following advantages: (i) it is insensitive to outliers due to the underlying Kalman filter, (ii) there is no need to arbitrarily choose the rolling-window size, (iii) no loss of observations, and (iv) it can be used for low frequency datasets (Antonakakis et al., 2020; Koop and Korobilis, 2013). We compare the results from both methods and conclude the policy implications.

The methodologies adopted in this study has some benefits. First, by employing a rolling-window technique, the applied methodology may track the degree of spillover effects over time without specifying a set of breakpoints or situations in advance. Second, we extend the DY connectedness to a dynamic approach based on TVP-VAR, which allows the variance-covariance matrix to vary via a Kalman filter estimation with forgetting factor[29]. Third, the spillover measure can be simply aggregated by both RW-VAR and TVP-VAR, allowing for the quantification of diverse spillover effects. Both measures enable for differentiating between net shock transmitters and net shock receivers, which in turn helps obtain a better knowledge of the underlying dynamics and improves the formulation of policy implications.

One recent papers closely related to our study is Uribe et al. (2020). This paper examined the integration and the propagation of shocks in the interconnected market of Nord Pool, they found that total spillovers in Nordpool have increased markedly since 2015, signaling greater power market integration. Their results shown that Norway and Sweden, as net transmitters of volatility, received fewer spillover than the other countries. With the same motivation, we restricted our markets to Denmark, Finland, Norway, and Sweden while Uribe et al. (2020) included Estonia, Latvia, and Lithuania. Regarding data, Uribe et al. (2020) has selected data ranging from 2013-2018 and restricting Norwegian's five bidding prices to one. However, we study longer sample period, from 2010-2022, in which covered a wide range of market events

[29] Kalman filter approaches have several desirable properties; e.g., they are fast because state space models encapsulate the Markov property and reduce to a set of recursions. And the forgetting factor approaches have been commonly used with state space models; they do not require the use of Markov Chain Monte Carlo, which can be computationally demanding (Antonakakis et al., 2020; Koop and Korobilis, 2013; Dangl and Halling, 2012). Supporting the main purpose of our study — to empirically examine the interdependency among global carbon markets — the detailed algorithm of the TVP-VAR model with the use of Kalman filter and forgetting factors can be found in Koop and Korobilis, 2013. Different measures, for example, the rolling window VAR analysis, will be provided in the robustness checks.

and regulatory changes. We argued that the due to the congestion issue between southern and northern Norwegian grid, the Norwegian's sic bidding prices should be divided to two prices, southern and northern price (see section 3.4 for detailed explanation). Furthermore, we go one step further and study whether carbon price can explain connectedness.

3.3 Methodology

The central research question of our study is how volatility connectedness (also known as spillover) in Nordic electricity markets respond to carbon price changes. Following the recent connectedness literature (see e.g., Apergis et al., 2017; Do et al., 2020; Han et al., 2020). In the following, we provide a brief overview of the approach. Section 3.1 applies Diebold and Yilmaz (2009, 2012) spillover method to estimate volatility spillover effects in NordPool. Section 3.2 constructs the TVP-VAR to estimate the volatility spillover effects. The two methods are based on using forecast error variance decomposition from VAR model. Section 3.3 displays the spillover measures. And Section 3.4 investigates the impact of the carbon cost on this volatility connectedness.

3.3.1 Rolling window VAR model

Diebold and Yilmaz (2012; 2014) utilized a generalized VAR approach to investigate the interdependence across the variables. The generalized VAR approach overcomes the Cholesky-type VAR in their previous paper, Diebold and Yilmaz (2009). The connectedness approaches are built from the variance decomposition matrix of a N-variable VAR(p) approximating model, see Equation (1) below:

$$X_t = \sum_{i=1}^{p} \Phi_i X_{t-i} + \epsilon_t,\ \epsilon_t \sim N(0, \Sigma_\epsilon), \quad (1)$$

Φ_i is $N \times N$ matrix of polynomial coefficients. ϵ_t is a vector of independently and identically distributed error terms, where the Σ_ϵ is the variance-covariance matrix for ϵ_t. In our study, N=5 for five regional markets and t refers to the date (i.e., daily time series) The VAR(p) should be covariance stationary. The DY connectedness is based on generalised impulse response functions (GIRF) and generalised forecast error variance decompositions (GFEVD), which were developed by Koop et al. (1996) and Pesaran and Shin (1998). The important step to calculate the GIRF and GFEVD is to transform the VAR to its moving average representation – VMA. The moving average coefficients are important to a VAR system's dynamics, since the variance decompositions rely on transformation of these original parameters, hence the key to understanding the dynamics of the system (Diebold and Yilmaz, 2012). We transform the VAR(p) model to its VMA and show in Equation (2) below:

$$X_t = \sum_{i=0}^{\infty} A_i \epsilon_{t-i}, \quad (2)$$

where A_i are $N \times N$ coefficient matrices, and subject to the recursion $A_i = \phi_1 A_{i-1} + \phi_2 A_{i-2} + \cdots + \phi_p A_{i-p}$, where $A_o = I_N$ ($N \times N$ identify matrix) and $A_i = 0$ for $i < 0$. These moving average coefficients measure the effects of shocks on variables X_t at different points in time.

The variance decompositions allow us to assess the fraction of the H-step-ahead error variance in forecasting X_n that is due to shocks to X_m, $\forall\, n \neq m$, for each n. Specifically, for each variable X_n, $(n = 1,2, \ldots, N)$ we can analyze which fraction of the error variance in forecasting X_n can be attributed to shocks to variable X_m. However, the decomposition of forecast error variance prerequisites isolated shock, yet energy market data often display contemporaneously associated shocks or innovations. Diebold and Yilmaz (2012) adopted the generalized VAR framework of Koop et al. (1996) and Pesaran and Shin (1998). This approach allows for correlated shocks but accounts for them appropriately using the historically observed distribution of the errors; circumventing the variables ordering problem of the identification schemes based on Cholesky factorization. Note, as the shocks to each variable are not orthogonalized, the sum of contributions to the variance of forecast error is not always equal to one. Denoting the H-step-forecast error variance decompositions by $\theta_{nm}^{g}(H)$, for $H = 1,2, \ldots, N$ (the contribution of variable *m's* shocks to *n's* generalized forecast error variance, θ_{nm}^{g} (H)), we have Equation (3) below:

$$\theta_{nm}^{g}(H) = \frac{\sigma_{mm}^{-1} \sum_{h=0}^{H-1} (e_n' A_h \Sigma_\epsilon e_m)^2}{\sum_{h=0}^{H-1} (e_n' A_h \Sigma_\epsilon A_h' e_n)}, \quad (3)$$

and normalized as

$$\tilde{\theta}_{nm}^{g}(H) = \frac{\theta_{nm}^{g}(H)}{\sum_{m=1}^{N} \theta_{nm}^{g}(H)} \times 100\%, \quad (4)$$

Where g refers to the generalized variance decomposition method. Σ_ϵ is the variance covariance matrix for ϵ_t. The moving average coefficient matrix corresponding to lag h is denoted *as* A_h. σ_{mm} is the *m-th* diagonal element in Σ_ϵ, which denotes the standard deviation of the shocks for the variable m (error term for the *mth* equation). e_n and e_m are both the selection vectors both the *n-th* entry for e_n and m-th entry for e_m are equal to 1, and 0 otherwise.

Then we normalized each entry of the variance decomposition matrix by the row sum as Equation (4), where the decomposition $\tilde{\theta}_{nm}^{g}(H)$ measures the spillover from X_m to X_n (X_t is a vector of volatility series for one of the Nordic electricity markets). Note that the $\sum_{m=1}^{N} \tilde{\theta}_{nm}^{g}(H) = 1$ and $\sum_{n,m=1}^{N} \tilde{\theta}_{nm}^{g}(H) = N$ by construction. The denominator represents the cumulative effect of all the shocks, while the numerator illustrates the cumulative effect of a shock in variable i.

3.3.2 TVP-VAR model

This section follows the approach of Antonakakis et al. (2020). The objective is to provide a flexible framework for the estimation and interpretation of time variation in the systematic and non-systematic parts of carbon markets and their effects on the rest of the markets. The TVP-VARs are state space models and one of the advantages is that statistical methods for state space models (based on the Kalman filter) are available. To describe the dynamics of volatility spillovers, the baseline TVP-VAR model is set as follows:

$$X_t = Z_{t-1}\mathrm{B}_t + \epsilon_t, \quad \epsilon_t|\Omega_{t-1} \sim N(0, \Sigma_t), \quad (5)$$

$$vec(\mathrm{B}_t) = vec(\mathrm{B}_{t-1}) + \xi_t, \ \xi_t|\Omega_{t-1} \sim N(0, \Xi_t), \quad (6)$$

$$\text{where } Z_{t-1} = \begin{pmatrix} X_{t-1} \\ X_{t-2} \\ \vdots \\ X_{t-p} \end{pmatrix}, \text{ and } \mathrm{B}_t = \begin{pmatrix} B_{1t} \\ B_{2t} \\ \vdots \\ B_{pt} \end{pmatrix}.$$

In the above models, p is the lag order, t is the sample length of the model, and $t = p + 1, p + 2, \dots, T$. Ω_{t-1} represents all information available until $T = t - 1$. X_t is an $N \times 1$ vector containing observations on N time series variables. Z_{t-1} represents $N \times p$ matrix. B_t are $N \times Np$ dimensional coefficient matrices while B_{it} are $N \times N$ matrices. ϵ_t and Σ_t are $N \times 1$ and $N \times N$ matrix, respectively. In equation (4), $vec(B_t)$ is the vectorisation of B_t which is an $N \times Np$ dimensional vector. The ξ_t is an $\mathrm{N}^2 p \times 1$ dimensional vector. Moreover, Ξ_t are $\mathrm{N}^2 p \times \mathrm{N}^2 p$ time-varying variance-covariance matrices; ϵ_t and ξ_s are independent of one another for all s and t. The equation (6), which models the evolution of B_t can be interpreted as a hierarchical prior for B_t.

For the initialization of Kalman filter, we utilize an uninformative prior for parameters Σ_o and B_o. The mean and the variance of B_0 are chosen to be the OLS point estimates ($\hat{B}_{OLS}$) and its variance Σ_{OLS}^{B} in a time invariant VAR. Consequently, the Kalman filter technique relies on a forgetting factor that regulates the variation of calculated parameter coefficients with time. As proposed by Koop and Korobilis (2014), the forgetting factor is adjusted at 0.99 given that our parameters do not change considerably across periods. The time-varying coefficients and error covariances are used to estimate the generalised connectedness procedure of DY's spillover index. We transformed Equation (7) to its VMA below:

$$X_t = \sum_{i=0}^{\infty} \Upsilon_{i,t}\, \epsilon_{t-i}, \quad (7)$$

where $\Upsilon_{i,t} = C_{1,t}\Upsilon_{i-1,t} + C_{2,t}\Upsilon_{i-2,t} + \ldots + C_{p,t}\Upsilon_{i-p,t}$. $\Upsilon_t = [\Upsilon_{1,t}, \Upsilon_{2,t}, \Upsilon_{3,t}, \ldots, \Upsilon_{p,t}]'$ and$C_t = [C_{1,t}, C_{2,t}, C_{3,t}, \ldots, C_{p,t}]'$. Both the $C_{i,t}$and $\Upsilon_{i,t}$ are $N \times N$ dimensional matrices. The H-step-forecast error variance decompositions process can be referred to Equation (3) and (4) above.

3.3.3 Spillover measures

Using the GFEVD (Equation (3) and (4)), we construct the below spillover measures:

Total connectedness index ($TCI_t(H)$): $\frac{\sum_{\mathrm{n,m=1,n\neq m}}^{N} \tilde{\theta}_{nm,t}^{g}(H)}{\sum_{\mathrm{n,m=1}}^{N} \tilde{\theta}_{nm,t}^{g}(H)} \times 100$, (8)

Directional Spillovers To ($TO_{n\to m,t}(H)$): $\sum_{n=1,n\neq m}^{N} \tilde{\theta}_{nm}^{g}(H)$, (9)

Directional Spillovers From ($FROM_{n\leftarrow m,t}(H)$): $\sum_{m=1,n\neq m}^{N} \tilde{\theta}_{nm}^{g}(H)$, (10)

Net Spillovers ($NET_{nm,t}$): $TO_{n\to m,t}(H)$- $FROM_{n\leftarrow m,t}(H)$, (11)

Net pairwise spillovers ($NPS_{nm}(H)$): $\left(\frac{\tilde{\theta}_{nm}^{g}(H)}{\sum_{\mathrm{k=1}}^{N} \tilde{\theta}_{nk}^{g}(H)} - \frac{\tilde{\theta}_{mn}^{g}(H)}{\sum_{\mathrm{k=1}}^{N} \tilde{\theta}_{jk}^{g}(H)}\right) \times 100$, (12)

3.3.4 The effect of carbon price on volatility spillovers

Next, we build a regression model to analyze the relationship between carbon price and the volatility spillovers across the NordPool market. Other potential effects on volatility spillovers are controlled, namely, gas price and oil price.

$$y_t = \alpha + \beta_1 Carbon_t + \beta_2 Gas_t + \beta_1 Oil_t + \upsilon_t, \quad (13)$$

Where y_t is the total connectedness index (TCI) calculated in Equation (8). $Carbon_t$ denotes the European Union Allowances spot prices, under European emission trading scheme (EU ETS). υ_t refers to the error term of the regression model.

3.4 Data

This paper first examines the price volatility and its spillover effects across Nordic electricity wholesale markets. The considered markets include four countries, with 12 bidding areas, which are Denmark (DK1-WesternDenmark, DK2-EasternDenmark), Norway (NO1-Oslo, NO2-Kristiansand, NO3-Trondheim, NO4-Tromsø, NO5-Bergen), Sweden (SE1-Lulea, SE2-Sundsvall, SE3-Stockholm, SE4-Malmo), and Finland. We obtain a rich sample of 107,352 hourly prices for each of the region, ranging from 1 January 2010 - 31 March 2022, collected from NordPool[30]. All the prices are quoted in EUR/MWh and aligned in terms of time zone.

Uribe et al. (2020) identified an at least 80% correlation between the prices of each area per country (Denmark, Sweden, and Norway), hence restricted their analysis to a single area. However, their sample ranges from 2013 to 2018, which is shorter than our sample. Electricity prices in our sample period may have different characteristics, so we first performed correlation tests across bidding areas within one country, the correlation between the hourly prices in areas of Denmark, Norway, and Sweden is 83%, 66% (average), 77% (average), respectively[31]. Specifically, DK1 and DK2 are highly correlated so we calculate the average hourly price as a proxy of wholesale electricity price in Denmark. Similarly, we average four prices across Sweden as a proxy of Swedish electricity price[32]. As for Norway, the price difference between southern and northern/central Norway are massive due to i) water reservoir in southern Norway is incredibly low, ii) southern Norway has exported large amounts of energy to the continent, resulting in the supply unable to meet demand, and iii) the little transmission capacity from the north to the south, a price bottleneck as well as the differences appeared. Hence, we average the NO1, NO2, NO5 (which are 98% correlated), and NO3 and NO4 (which are 97% correlated) as two representatives of Norwegian (Southern and Northern) price, respectively. In short, as an extension to the literature the Nordic market integration (e.g., Uribe et al., 2020), this paper uses five regional wholesale prices in the following model. Table 2 presents the descriptive statistics of the calculated prices for the five areas – Denmark, Finland, Norway South, Norway North, and Sweden.

Table 2. Descriptive statistics – Hourly price of five study areas

	Mean	Minimum	Maximum	Std.Dev	Skewness	Kurtosis	Obs

[30] Intraday electricity prices are obtained from the NordPool website, https://www.nordpoolgroup.com/services/power-market-data-services/.

[31] Tables for correlation tests can be found in Table A2-A4 in Appendix A.

[32] Note, that series of SE1 – Lulea and SE2- Sundsvall have 98,315 identical hourly prices, hence the correlation between these two is almost equal to 1.

Denmark	43.06	-200.00	1052.50	36.65	6.24	78.36	107,339
Finland	43.18	-1.73	1400.11	31.46	9.52	228.41	107,339
Norway South	38.40	-0.88	667.92	28.80	3.93	34.48	107,339
Norway North	34.01	-0.01	1400.11	21.12	16.20	810.27	107,339
Sweden	38.11	-1.97	1400.11	24.37	11.68	459.67	107,339

Source: Own elaboration based on data from Nordpool. Note: Sample including electricity wholesale prices series from Denmark, Finland, Norway, and Sweden from January 1,2010 - March 31, 2022.

Daily realized volatilities (RV, hereafter) are estimated based on the hourly electricity spot price. Following Frömmel et al. (2014), the realized variance is defined as the summation of the squared price changes over day t (see among others, Andersen et al., 2001; Do et al., 2020). Hence, the RV is defined as Equation (14) below:

$$RV_t = \sqrt{\sum_{j-1}^{M} r_{t,i}^2}, \quad \mathrm{i} = 1, \ldots \mathrm{M}, \mathrm{t} = 1, \ldots, \mathrm{T}, \quad (14)$$

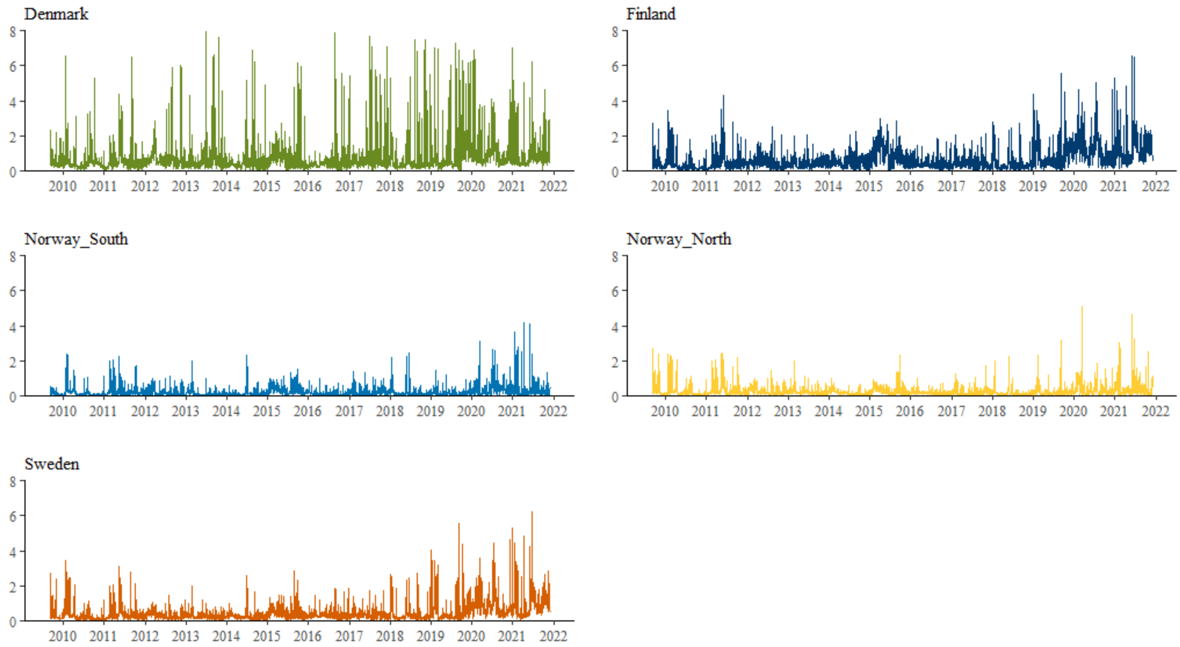
Where $r_{t,i}$ denotes the log price change from hour i-1 to i on day t. The sampling frequency is 1-hour and M=24 in our case. Table 3 displays the descriptive statistics of daily volatilities of five areas. Fig. 1 plots the daily volatilities of five study areas.

Table 3. Descriptive statistics – Daily volatilities of five study areas

	Mean	Minimum	Maximum	Std.Dev	Skewness	Kurtosis	ADF	Obs
Denmark	0.758	0.039	10.726	1.013	4.649	26.917	-24.69***	4473
Finland	0.668	0.029	6.558	0.625	2.533	10.552	-14.65***	4473
Norway South	0.222	0.007	4.150	0.298	4.707	34.438	-22.83***	4473
Norway North	0.261	0.014	5.065	0.316	4.673	36.287	-19.62***	4473
Sweden	0.459	0.018	6.234	0.515	3.530	19.039	-17.80***	4473

*Source: Own elaboration based on data from Nordpool. Note: Daily realized volatility is measure by Equation (X) above. The electricity daily volatilities from five regions – Denmark, Finland, Norway South, Norway North, and Sweden from January 1 2010 –to March 31 2022, including 4473 daily observations. The hypothesis of the Augmented Dicky Fuller (ADF) test is H_0: non-stationary against H_1 : stationary. The lag length is determined by BIC criterion. * denotes significance at 10% level, ** denotes significance at 5% level, *** denotes significance at 1% level.*

Figure 1. Plots of daily volatilities of five study areas



Source: Own elaboration based on data from Nordpool. Note: Daily realized volatility is measure by Equation (10) above. The electricity daily volatilities from five regions – Denmark, Finland, Norway South, Norway North, and Sweden cover the period January 1, 2010 – March 31 2022, including 4473 daily observations.

As can be observed from Table 3 and Figure 1, price volatility in Norway is generally lower than the other three countries, while volatility in Denmark shows the highest. Around 95 percent Norway's electricity generation is from hydropower, and this has given Norway a stable access to inexpensive clean energy. However, for Denmark, its electricity is largely relied on wind power, which is a highly intermittent energy resource and easily affect by weather conditions, hence, higher volatility is expected. All five series are tested stationary, be Augmented Dickey Fuller test (Dickey and Fuller, 1979).

3.5 Results

In this section we report the results of empirical analysis by the methods presented in Section 3.3. In the following empirical model, we use fourth-order VARs (p=4) (selected by Schwarz information criterion), with 10-step-ahead forecasts [33] (H=10). We define the total connectedness index (TCI) by summing all non-diagonal elements of the generalized variance matrix. We define that if this TCI rises, so does network member dependency, therefore higher

[33] A different choice of forecasting horizon, H from 2 to 9 will be assessed in the robustness check in the Appendix D. Following most of the literature (see for example Yilmaz, 2009), we use 10-step-ahead horizon in the main text.

market risk. On the other hand, if the TCI decreases then the dependence between the members decreases and in turn the market risk decreases.

3.5.1 TVP-VAR estimation

3.5.1.1 Total connectedness index

This section reports the empirical results estimated by TVP-VAR. The outcomes corresponding to methodology provided in Section 3.3.2 and 3.3.3 are summarized below. Table 4 presents the averaged spillover effects among the markets, estimated by TVP-VAR model. Figures (2) – (6) present the dynamic 'total volatility connectedness', 'directional volatility spillovers to the system', 'directional volatility spillovers from the system', and 'net pairwise volatility spillovers', respectively.

The main diagonal of Table 4 shows own-variance shares of shocks, while the off-diagonal elements reflect the interaction across five markets. The number in the bottom right corner represents TCI of the system. As such, the average volatility TCI is 52.41%, indicating that 52.41% of the future volatility in NordPool is attributed to volatility shocks spreading across the markets. The internal cross-contribution due to individual shocks is the major driver of future performance across five regions in NordPool. Except for Denmark, all the total directional spillovers 'From Others' for Finland, Norway South, Norway North, and Sweden are larger than 50%. The largest value, 60.72%, is for Sweden, which means that electricity price in Sweden bears the largest shocks from other markets, while Danish electricity market receive the smallest shocks, 39.87%, from other markets in the system. As for volatility spillover 'To Others', Denmark transmitted 28.78% shocks to the system while Sweden transmitted in total 77.52% to the system. Observed from the last row of Table 4, the 'Net Total', Sweden act as a net transmitter to the system, which is 16.80% of the volatility spillovers, while the other four prices, as volatility spillover receivers, both show negative values. Denmark is the net spillover receiver who bear 11.10% volatility spillovers from the system.

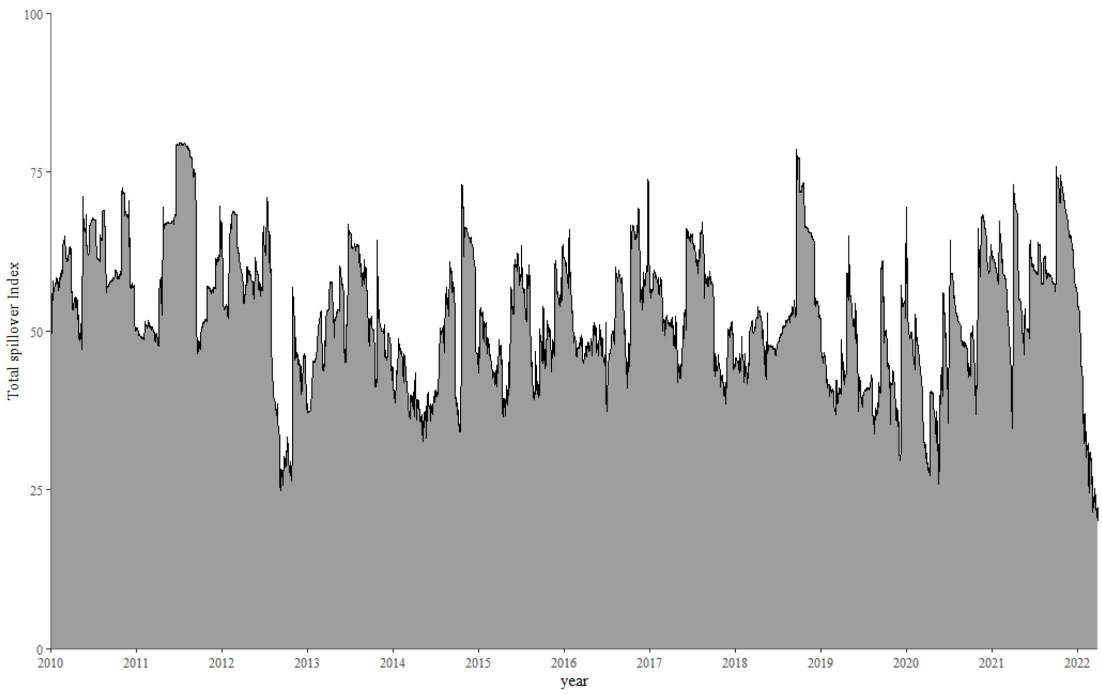
Compared to the literature, Ma et al. (2022) reported a 44.24% static volatility spillovers in the electricity market system of Europe, which is lower than our result of volatility spillovers in Nordpool. Their study included, for instance, United Kingdom, France, Poland, Nordpool, etc., electricity day-ahead markets. The lower volatility of connectedness is explained by the insufficient flows and limited grid interconnections across the whole Europe, while NordPool is an integrated market with larger non-local risks transmitted by other markets. Ma et al. (2022) concluded that, Denmark received the largest, 40.47% shocks from the system compared to the other NordPool markets - Finland, Norway, and Sweden. The view is different from ours where Denmark (Sweden) received the smallest (largest) shocks from the NordPool system. In their study, Denmark and Finland are both net shock receivers while Norway and Sweden are net shock transmitter. In our study only Sweden act as shock transmitter, as concluded above.

Table 4. Average connectedness matrix of the system – estimated by TVP-VAR

	Denmark	Finland	Norway South	Norway North	Sweden	From Others
Denmark	60.13	11.33	7.02	6.48	15.04	39.87
Finland	7.81	45.21	10.82	11.45	24.70	54.79
Norway South	6.21	11.38	47.04	18.02	17.35	52.96
Norway North	5.35	11.15	16.77	46.30	20.41	53.70
Sweden	9.41	20.92	13.35	17.04	39.28	60.72
To Others	28.78	54.78	47.97	53.00	77.52	**TCI=52.41**
Net Total	-11.10	-0.01	-4.99	-0.70	16.80	

Source: This spillover table is generated from 10-step-ahead generalized VAR forecast error variance decomposition estimated from TVP-VAR. The ij^{th} *entry estimates the fraction of 10-step-ahead error variance in forecasting market i due to exogenous shocks to market j (the spillover from market j to market i:* d_{ij}^{J} *). According to Equation 16 (*$C_{ij,t} = C_{i\to j,t}(J) - C_{i\leftarrow j,t}(J)$*), we obtain the net total directional connectedness,* $C_{ij,t}$*.*

Figure 2. Dynamic total volatility connectedness – estimated by TVP-VAR



In most previous studies, the evolution of price and volatility spillovers over time in electricity spot markets is often attributed to changes in physical conditions that can induce supply and demand shocks within the electricity market. The extent of price integration across European electricity markets are proved to be determined by market-specific factors and shocks in the short term, such as congestion (interconnector capacity) and extreme weather, the surge in demand, and changes in electricity market structure in the long run, such as changes in renewable energy shares, total generation capacity, and market reforms, as well as external shocks from the financial market, geopolitical events, etc. (Frömmel et al., 2014; Han et al., 2020; Kyritsis et al., 2017, Chuliá et al., 2019). Hence, we plot the dynamic volatility spillover evolutions to relate to the spillover changes to specific market events and policies, see Figure 2.

It is clear from Fig. 2, that the dynamic of the TCI fluctuates significantly, between 20.2% and 79.6%, which confirmed the necessity of using the TVP-VAR. Significant fluctuations of the TCI correspond to a series of local and global events: the transition of EU ETS from Phase II to Phase III in 2012, the European debt crisis in 2012, crude oil crisis from mid-2014 to 2015, the surge in the EU emission allowances price in 2018, market coupling of GB-Irish market in 2018, and the COVID-19 pandemic.

Specifically, we observed that the first plunge of the TCI happened in the second half of 2012 from July to September, jumping from 65.15% to 24.83%, and goes back to around 55% in November . Intuitively, the fluctuation is contributed by the European debt crisis and EU ETS's transition. The EU ETS was transitioning from Phase II (2008-2012) to Phase III (2013-2020) during the second half of 2012. Due to a large surplus of allowances from phase two, the demand for ETS allowances has decrease which cause a fall in EUA prices, from 30 Euro/emission allowance to 5 Euro/emission allowances. The TCI is found to indicate responses to this event, reflecting a lower market risk when there was a surplus of emission allowances product.

We observed a slight trend of increase in the year 2018, followed with a huge spike in September 2018. Upon investigation, in September 2018, the NordPool launched the GB-Ireland power market coupling, having played a key role in ensuring the islands of Ireland's coupling with the rest of Europe. The joining of new market typically induced the more competition in NordPool, as well as the GB-Ireland market, hence the arising market risk in NordPool.

The outburst of COVID-19 in the spring of 2020 has increased the risk level among Nordic electricity markets; TCI surged from 27.18% in April 2020 to 73.54% in October 2021. Moreover, there is an increase in TCI from mid-2020 to the end of 2021. In the post Covid-19 economic recovery period, prices of natural gas, electricity, and carbon are steeply increasing when energy demand rose. The surge in demand for energy was not matched with increased supplies, and the importing regions competed with one another in the global energy market. The economic consequences of an electricity supply shortage worsened as the 2021 winter arrived. It confirms that Covid-19 and the post-Covid economic recovery have increased the market risk. However, from the end of 2021, Nordic electricity were able to be recovered from Covid-19 pandemic as the wind generation has rapidly risen in Nordic countries; and Norway had more rainfall that eventually its reservoirs reached their highest point since 2015 (Matt, 2022). There is no acute risk of shortages or supply disruptions in the electricity supply in the four countries when the year 2022 started.

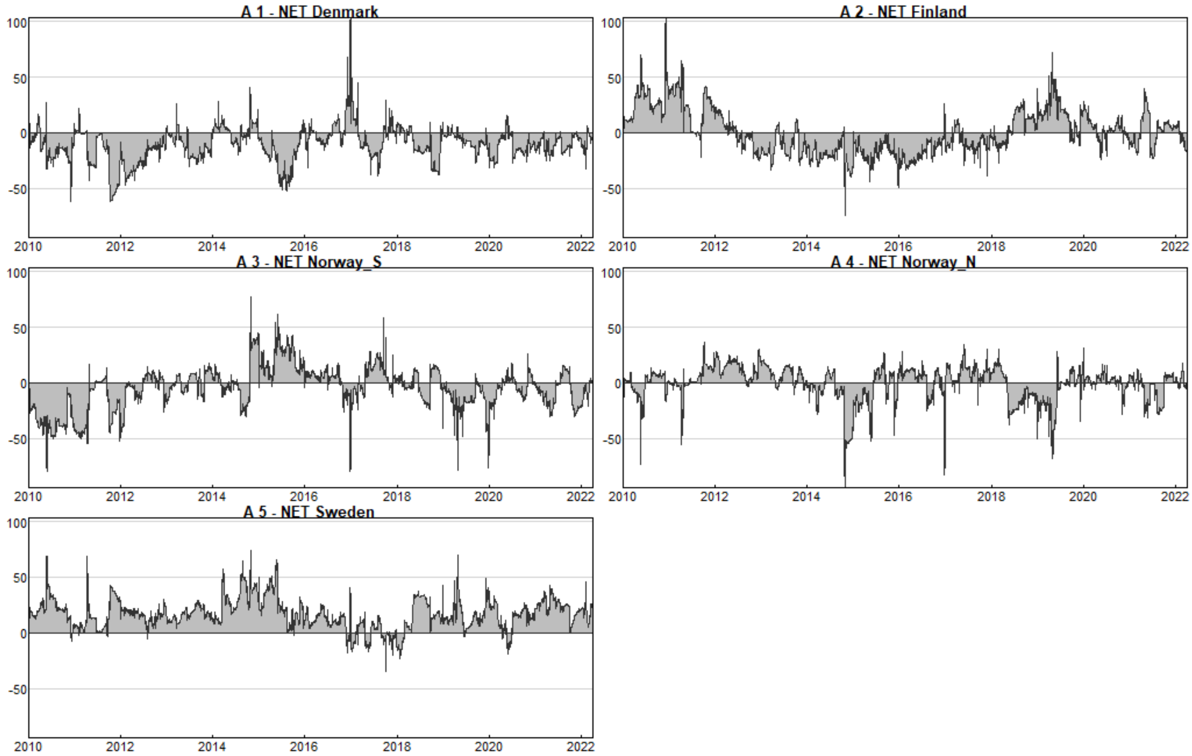
3.5.1.2 Net directional spillover analysis

To investigate the directional dynamic spillovers for each market in the NordPool, Figure 3 plots the net spillovers with regards to Equation (11) in Section 3.3.3 ($NET_{nm,t} = TO_{n\rightarrow m,t}(H)$-$FROM_{n\leftarrow m,t}(H)$), and corresponding to the last row of Table 4, "Net Total". Figure 4 plots the net pairwise volatility spillover that corresponds to Equation (12) in Section 3.3.3. The net pairwise volatility spillover between market n and m is the difference between gross volatility shocks transmitted from market n to m and gross volatility shocks transmitted from m to n (Diebold and Yilmaz, 2012b).

Now we start the result analysis from Denmark. Figure 3 indicates that Denmark is the net volatility spillover receiver over the sample, except for relatively small episodes, for example, a short period of being a volatility transmitter at the end of 2016. This is consistent with the averaged results in Table 4, which shows Denmark is the largest receiver of volatility spillover. Figure 4 further indicates that Sweden acts as a net transmitter of shocks to Denmark during the sample period (see Figure 3, Denmark-Sweden). From 2010 and early 2014, Denmark is the net spillover receiver that bears the shocks from Finland, Norway south, Norway north, and Sweden. There are some exceptions when Denmark acts as a volatility spillover transmitter. For example, it transmitted shocks to Finland in 2016 and to Southern Norway at the end of 2016. Since Denmark is the country that has the largest share of wind power electricity in the generation mix, the effect of wind on price volatility is higher. The country relied on importing hydroelectricity from Norway and Sweden, hence the position of shock receiver confirmed reasonably.

The second largest volatility spillover receiver shown in Table 4 is Southern Norway. Southern Norway is an interesting case in NordPool as its water reservoir is incredibly low and exported large amounts of electricity to the rest of European electricity market, resulting in supply and demand unbalance. It is also connected to Western Denmark, where the power generated are based on wind power while Southern Norway has relied on hydro power. Benefit from the flexibility of being a hydro producer while connected to a Danish wind power generation, Southern Norway imported wind electricity from neighboring country when the cost of import is lower than produce. Figure 3 shows that Southern Norway acts as a net spillover receiver of the network, from 2010 to 2013, and 2016 to 2022.

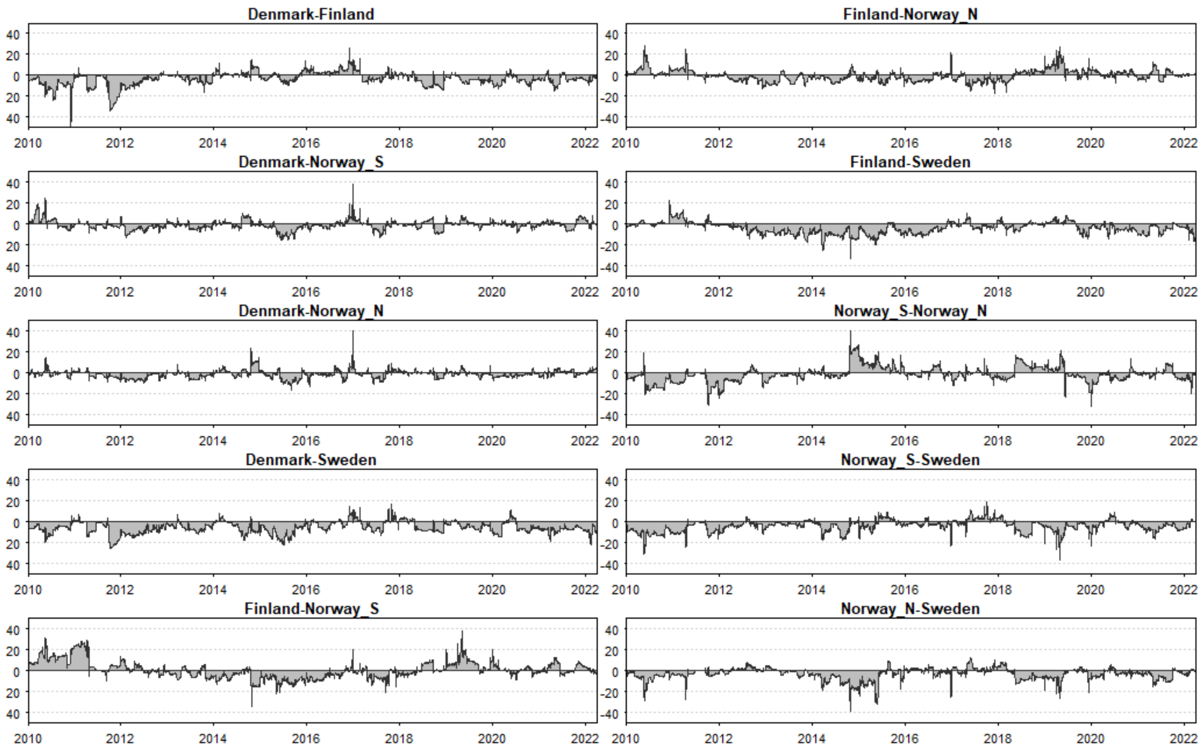
Figure 3. Net volatility spillovers - estimated by TVP-VAR



Northern Norway is a small net receiver of volatility spillover at an aggregated level. As can be observed from Figure 3-A4, from the second half of 2011 to 2014, Northern Norway was a shock transmitter to the system, as well as during 2015 and 2018. In the rest of the sample period, Northern Norway acts as the significant shock taker; it received 93.77 percent volatility from the NordPool network on 27 Oct 2014. As for the net pairwise spillover shown in Figure 4, we further observed that Northern Norway was mainly the shock transmitter to Northern Norway from 2010 to 2015 and Finland from 2012 to 2018. In the meantime, net spillovers received by Northern Norway especially came from Sweden (2010-2015), Southern Norway (2015-2016), and Finland (2019-2020).

Finland is classified as a net volatility spillover transmitter as it receives 54.79 percent spillover effect from the system and transmits 54.68 percent to the system (see Table 4). The dynamic plots of net spillovers in Figure 3 and net pairwise spillovers in Figure 4 indicate that the net position changed through the sample. Finland was a net transmitter between January 2010 and June 2012, mainly to Norway, then it was a net spillover receiver from June 2012 to June 2018, mainly from Sweden and Norway. The view is slightly different from Uribe et al. (2020), who concluded that Finland received volatility shocks from Norway during 2013 and 2015. Since 2018, Finland went back to being a spillover transmitter to Denmark and Norway; however, the effect was lower than that of 2010 to 2012. It is worth noting that Sweden persistently transits net spillover to Finland throughout the whole sample. Finland is a net importer of electricity from Sweden

Figure 4. Net pairwise volatility spillovers - estimated by TVP-VAR



3.5.2 Rolling window VAR estimation

This section follows the Diebold and Yilmaz (2012)'s rolling window five-variable VAR model to estimate the volatility connectedness in NordPool markets. According to the Schwarz information criterion (SIC), the optimal lag length is set as p=4. Horizon is set to 10-step-ahead forecasts and rolling window size 200.

3.5.2.1 Total connectedness index estimated by RW-VAR

Table 5 shows the variance decomposition matrix. The main diagonal of Table 5 shows own-variance shares of shocks, while the off-diagonal elements reflect the interaction across five markets. According to the results in Table 5, we can find that the total connectedness index (TCI) is 50.92 percent, slightly lower than the TCI estimated by TVP-VAR. In an aggregated level, Sweden transmits the largest, 10.99 percent, net volatility spillovers to the system. The Swedish electricity wholesale market produces and receives the most volatility spillovers to other markets (72.38%) and from other markets (61.38%) at an aggregated level. Compared to the TVP-VAR estimation, Sweden transmitted 5.14 percent less net spillover to the system in an RW-VAR. Danish electricity wholesale market produces and receives the least volatility spillover from (33.63%) and to (22.31%) the system; the view is consistent with the TVP-VAR measure. In terms of net volatility spillover, Denmark is a net receiver (-11.32%). The estimated value is almost the same as the TVP-VAR's result for Denmark. Southern Norway receives 51.55 percent volatility spillover from other markets and produces 51.12 percent volatility spillovers to the system, making it a net volatility spillover receiver in an averaged measure (-0.43%). However, Northern Norway is classified as a net volatility spillover producer; this result differs from the result estimated by TVP-VAR, which shows Northern Norway is a net producer of spillover. Finland receives the second most significant value of spillover, 54.47 percent from the other four markets, and overall classified as the second largest net volatility spillover in an aggregated level (-3.39%).

Table 5. Average connectedness matrix of the system - estimated by 200 days rolling window

	Denmark	Finland	Norway South	Norway North	Sweden	From Others
Denmark	66.37	8.24	7.5	6.12	11.77	33.63
Finland	6.26	45.53	10.85	13.43	23.93	54.47
Norway South	4.67	10.64	48.45	19.25	16.99	51.55
Norway North	4.06	12.35	17.44	46.46	19.68	53.54
Sweden	7.31	19.85	15.32	18.89	38.62	61.38
To Others	22.31	51.08	51.12	57.69	72.38	**TCI=50.92**
Net Total	-11.32	-3.39	-0.43	4.15	10.99	

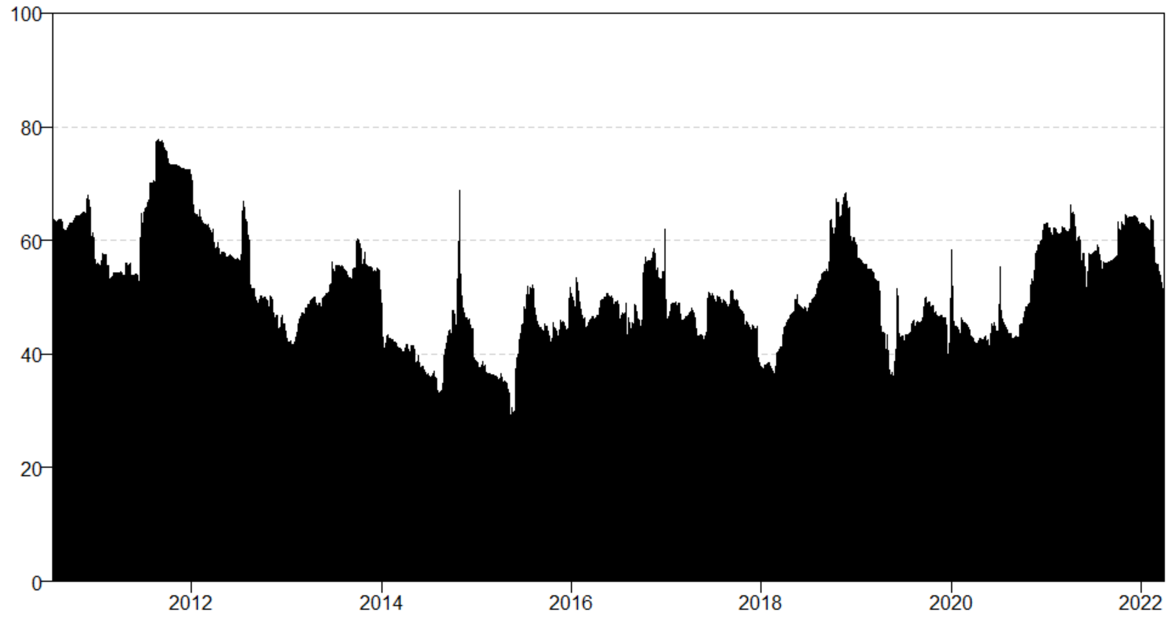
Source: This spillover table is generated based on 10-step-ahead generalized VAR forecast error variance decomposition estimated from 200 days rolling window VAR. The ij^{th} *entry estimates the fraction of 10-step-ahead error variance in forecasting market i due to exogenous shocks to market j (the spillover from market j to market i:* d_{ij}^{J} *). According to Equation 16 (*$C_{ij,t} = C_{i\to j,t}(J) - C_{i\leftarrow j,t}(J)$*), we obtain the net total directional connectedness,* $C_{ij,t}$*.*

In Figure 5, we present the dynamic total connectedness measures of the 200 days rolling-window VAR approach. It can be observed that the pattern of the TCI is less volatile than that estimated by the TVP-VAR. TCI fluctuates between 77.70% and 27.12%. Two major patterns can be found and concluded from those time variations, which will be descried as follows:

i) A trend of decrease in TCI is observed from July 2010 to May 2015. It shows, in general, the volatility spillovers within NordPool markets gradually decreased after the 2008-2010 financial crisis and the 2010-2012 European debt crisis. Three spikes were found during this period; the first spike (77.69%) was observed on 25 August 2011, following the European debt crisis. The second one, reaching 60.33% on 1 October 2013, appeared after a large price fall of emission allowances under EU ETS. The fall in emission prices promoted the thermal production of fossil fuel resources and affected the value of water negatively. Since thermal power is the opportunity cost of flexible hydropower with a reservoir, the decline in emission prices drove the power prices down. It raised the short-term volatility spillover level in the NordPool (NordREG, 2014). The last spike appears on 26 October 2014, reaching 68.88%, corresponding to the plunge in crude oil prices during 2014. Intuitively, we can state that the dependence on the NordPool wholesale electricity market increased when the crude oil market price plunged, but TCI decreased to 27% on 14 May 2015 after the crisis had eased.

ii) During the second half of the sample, the TCI mainly fluctuates around 40%–60%, with a few exclusions. The launch of the GB-Ireland market coupling in September indeed raised the spillover effect in NordPool. We observed a steep increase from September 2018 and a spike of 68.35% on 22 November 2018. Again, the Covid-19 outburst doesn't affect the volatility spillover effects in Nordpool immediately but raised the level of spillovers from September 2020 and peak at 66.12% on April 2021, during the post pandemic economy recovery.

Figure 5. Dynamic total volatility connectedness – estimated by 200 days rolling window DY2012



3.5.2.2 Net directional spillover analysis

Next, we investigate the net spillover for each market by the use of RW-VAR connectedness. Figure 6 plots the net volatility spillover in NordPool network with regards to Equation (11) in Section 3.3.3 ($NET_{nm,t} = TO_{n \to m,t}(H)$- $FROM_{n \leftarrow m,t}(H)$), and corresponding to the last row of Table 5, “Net Total”. Figure 7 thus plots the net pairwise volatility spillover. Main findings will be concluded below:

Denmark receives net volatility spillover from the system throughout the whole sample period. The volatility spillover mostly come from Sweden and Southern Norway. As for the net volatility transmitter, Sweden is being a net spillover producer to the system, especially to Denmark and Finland. However, the net pairwise volatility spillover between Sweden and Northern Norway changes all the time. In particular, between 2010 and 2018, Norway was the main contributor of the volatility spillovers that Sweden received; however, from 2018 to 2020 Sweden transmitted relatively large volatility spillovers to Northern Norway.

For Finland, the overall evolution pattern shows a similar trend as the TCI pattern measured by TVP-VAR. However, the position of net transmitter in the beginning of the sample was less powerful than that estimated by TVP-VAR. For example, the net volatility spillover transmitted by Finland to the system was reaching 66 percent in May 2010, however due to the loss of sample in the rolling-window, we cannot observe that value in May using the RW-VAR. The maximum value of net spillover the Finland produced was reaching 22.76% in July 2010 while the net spillover was reaching 32% in July 2010. Finland was a net volatility received between 2012 and 2018, as well as 2020 and 2022, the rest of the sample, it was being a spillover producer for short-term.

For Finland, the overall evolution pattern is similar to the TCI pattern measured by TVP-VAR. Finland was a net volatility transmitter from July 2010 to December 2011 and from August 2018 to January 2019. However, the position of a net transmitter was less powerful than that estimated by TVP-VAR from 2010 to 2011. For instance, the net volatility spillover transmitted by Finland to the system reached 66 percent in May 2010; however, due to the loss of sample in the rolling window, we cannot observe that value in May using the RW-VAR. The maximum value of net spillover Finland produced reached 22.76% in July 2010, while the net spillover reached 32% in July 2010.

Figure 6. Net volatility spillovers - estimated by 200 days rolling window

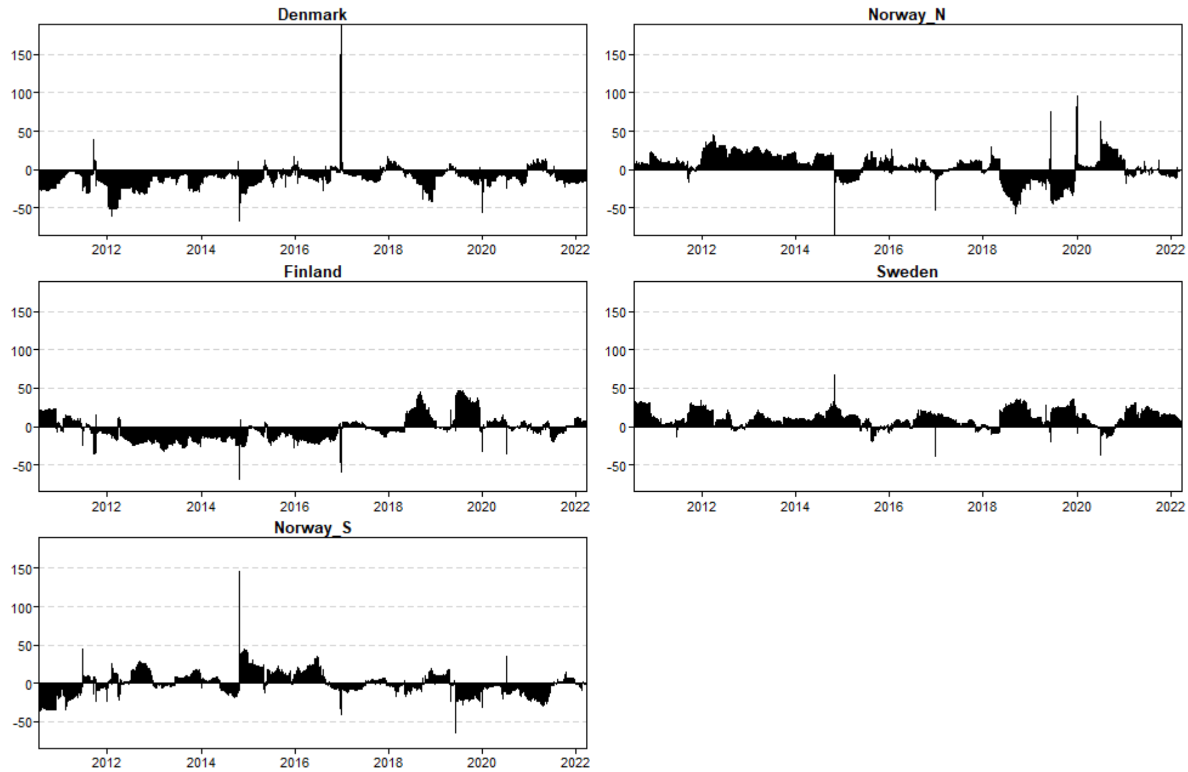
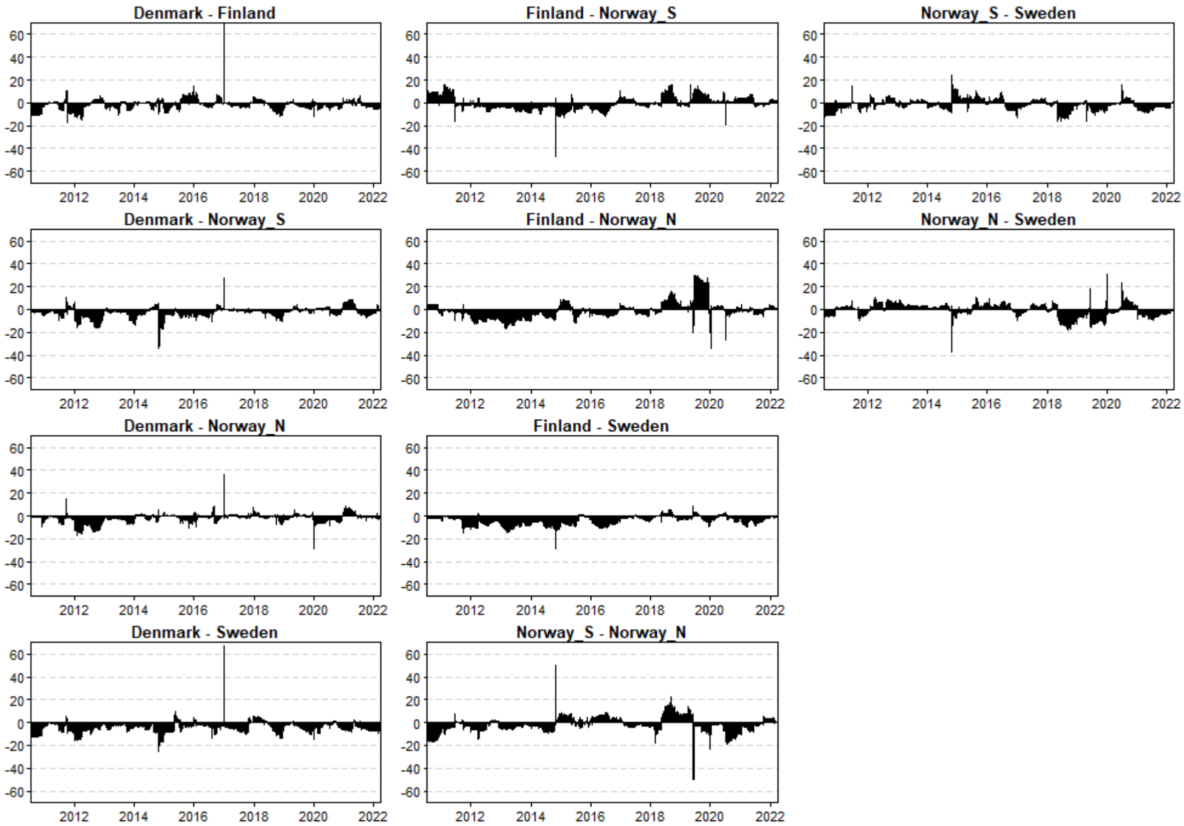


Figure 7. Net pairwise volatility spillover - estimated by 200 days rolling window



3.5.3 The effect of carbon price on volatility spillovers

The power industry is the first regulated sector in the EU ETS and is always the sector with the highest CO2 emissions and is the most significant carbon trading participant. Higher carbon prices encourage investment in clean power generation and less carbon-intensive technologies, whereas lower carbon prices revive the attractiveness of fossil fuel power generation. Electricity price volatility and spillover effects across the integrated electricity market depend on the EU's carbon price change. This section analyses the impact of the carbon price on the volatility of connectedness in NordPool wholesale electricity markets. According to Equation (13) in Section 3.3.4, Table 6 reports the result of carbon price impact on volatility spillover in Nordpool electricity markets. Following the literature, electricity prices can easily be affected by other energy prices, such as gas and crude oil prices; hence we control the gas and oil prices in the model. All data are used on a monthly frequency, from January 2010 to March 2022. The rolling-window estimation causes a loss in observation in the first window. We report the result from both 200-days rolling window VAR and 100-days rolling window VAR.

The result shows that the carbon price does not have significant impact on TCI estimated by TVP-VAR and 100-days rolling window VAR. However, the carbon price has 5% significant impact on TCI estimated by 200-days rolling window VAR. The positive relationship between carbon price and total volatility spillovers estimated by RW-VAR is observed. Meanwhile the crude oil price also has positive effect on TCI estimated by 200 days rolling window VAR, significance in 1% level.

Table 6. Impact of carbon price on volatility spillovers in NordPool

	Dependent Variable		
	TCI (TVP)	TCI (RW-200)	TCI (RW-100)
Carbon	0.175	0.164 **	1.309
	(1.033)	(0.058)	(1.025)
Gas	3.603	-0.031	1.626
	(2.192)	(0.150)	(2.173)
Oil	-1.594	0.100 ***	4.963
	(3.197)	(0.029)	(3.168)
Constant	51.045 ***	39.269***	26.515*
	(11.624)	(2.373)	(11.519)
Observations	147	141	144
R2	0.028	0.206	0.081
Adjusted R2	0.008	0.189	0.061
Residual Sta.Err	9.659	8.274	9.569
	(df=143)	(df=137)	(df=140)
F statistics	1.381	11.860***	4.090**

Note: *p<0.1; **p<0.05; ***p<0.01. The table presents the estimates of the impacts of carbon prices on total volatility connectedness index across five NordPool wholesale electricity prices. The dependent variables are disaggregated monthly total volatility spillovers estimated from both TVP-VAR and RW-VAR. standard error is reported in the parenthesis.

3.6 Conclusion

This paper examines price volatility and its spillover effects across Nordic electricity wholesale markets. The considered markets include four countries, with 12 markets, which are Denmark (DK1-Western Denmark, DK2-Eastern Denmark), Norway (NO1-Oslo, NO2-Kristiansand, NO3-Trondheim, NO4-Tromsø, NO5-Bergen), Sweden (SE1-Lulea, SE2-Sundsvall, SE3-Stockholm, SE4-Malmo), and Finland. We obtain a rich sample of 107,352 hourly prices for each of the region, ranging from 1 January 2010 to 31st March 2022, collected from NordPool. To study the above questions, the novelty of our approach is three folded. First, we use the connectedness approach based on both the TVP-VAR and RW-VAR models to analyse integration in Nordic electricity markets, contributing to the scare literature in the electricity volatility connectedness across four countries (Sweden, Finland, Denmark, Norway). Second, we divided Norwegian market to two prices due to the observed difference between northern and southern electricity prices. Thirdly, we examine how changes in carbon price influence those spillover effects.

Our results show that the average volatility TCI estimated by TVP-VAR (RW-VAR) is 52.41% (50.92%), indicating that 52.41% (50.92%) of the future volatility in NordPool is attributed to volatility shocks spreading across the markets. As for TVP-VAR measure, our results show that Sweden is the only net volatility spillover transmitter while Denmark bears the most significant shocks from the system. The dynamic evolution of total connectedness index responded to the EU ETS's transition from phase II to phase III, indicating that the decrease of market risk in NordPool corresponds to a surplus of emission allowances in EU ETS. In addition, the launch of GB-Irish power market coupling into NordPool increased the market risk in NordPool. The RW-VAR connectedness shows that both Sweden and Northern Norway are net volatility spillover transmitter at an aggregated level. Danish electricity wholesale market produces and receives the least volatility spillover from (33.63%) and to (22.31%) the system; the view is consistent with the TVP-VAR measure. A spike in total connectedness index appeared after a large price fall of emission allowances under EU ETS in 2013. The fall in emission prices promoted the thermal production of fossil fuel resources and affected the value of water negatively. Since thermal power is the opportunity cost of flexible hydropower with a reservoir, the decline in emission prices drove the power prices down. It raised the short-term volatility spillover level in the NordPool. The result further shows that the carbon price does not have significant impact on TCI estimated by TVP-VAR and 100-days rolling window VAR. However, the carbon price has 5% level significant impact on TCI estimated by 200-days rolling window VAR. The positive relationship between carbon price and total volatility spillovers estimated by RW-VAR is observed.

The findings of our study are beneficial for electricity market participants. In particular, our results show that volatilities in integrated Nordic wholesale electricity markets are affected by carbon prices, market coupling, public health event, and the production of neighboring regions.

Rolling window-based VAR connectedness estimation are defined in the literature sensitive to the choice of rolling-window size. Further research can be done by controlling more variable when testing the impact of carbon price on volatility spillovers in Nordic electricity wholesale markets. For instance, including economics policy uncertainty, extreme weather conditions in the control variables. Another one possibility is to test at different frequency of the model to obtain a more conclusive result.

Conclusion

Long-term goals for developing regional or nationwide ETS would be to create a larger, integrated, and more liquid carbon market. Through linking, some benefits emerge: i) economically, integrated carbon market increases cost-efficiency by accessing lower-cost abatement options and reduces the risks of carbon leakage, thus, preserving local competitiveness. ii) Politically, it may deepen the regional/global collaboration with strategic partners, and spur global climate action on markets. The cooperation and conflict in climate change negotiations has long been debated, linking the ETS might provide avenues for exploring alternative prospects in a less politicized or historically tense area. On the other hand, linking poses thorny political difficulties. Distributional challenges may develop, depending on who the linking partners are. Financial flows between jurisdictions can be politically contentious, which impose high complexity of regulations. The positive/negative outcome of the linking/delinking depends on the choice of partners, negotiation process, linking agreements, and the balance between liquidity and over-financialization.

Some countries in Europe, e.g., Sweden, Denmark, the UK, and Ireland, have introduced carbon taxes or climate change levies on top of the already existing ETS system. Regarding allocative efficiency of emissions, it should get weakly less efficient when the country overlays any complementary climate policy with a carbon price. However, there may be more desirable distributional impacts. The public acceptance of emissions trading programs may be jeopardized if the spatial distribution of pollution shifts in a way that makes minorities and low-income populations suffer most of the associated damages to human health and the environment. ex-post analysis, such as examining whether the carbon pricing widens or narrows the exposure gap between low-income populations and other communities would have an empirical and practical impact on policymakers and the wider public. Further questions for example, how to avoid green washing in the operation of carbon pricing is worthwhile investigating.

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Appendix A

Table A1. Definitions of variables

Variable	Definition
BEAPrice	Beijing Emission Allowances weekly/monthly average price
SHEAPrice	Shanghai Emission Allowances weekly/monthly average price
GDEAPrice	Guangdong Emission Allowances weekly/monthly average price
SZEAPrice	Shenzhen Emission Allowances weekly/monthly average price
HBEAPrice	Hubei Emission Allowances weekly/monthly average price

Notes: Original daily data convert to monthly by calculating the mean of the month. The sample period covers from 2014-28-04 to 2019-25-12. BEAPrice, SHEAPrice, GDEAPrice, SZEAPrice, and HBEAPrice denote the carbon emission allowances price for Beijing ETS, Shanghai ETS, Guangdong ETS, Shenzhen ETS, and Hubei ETS, respectively.

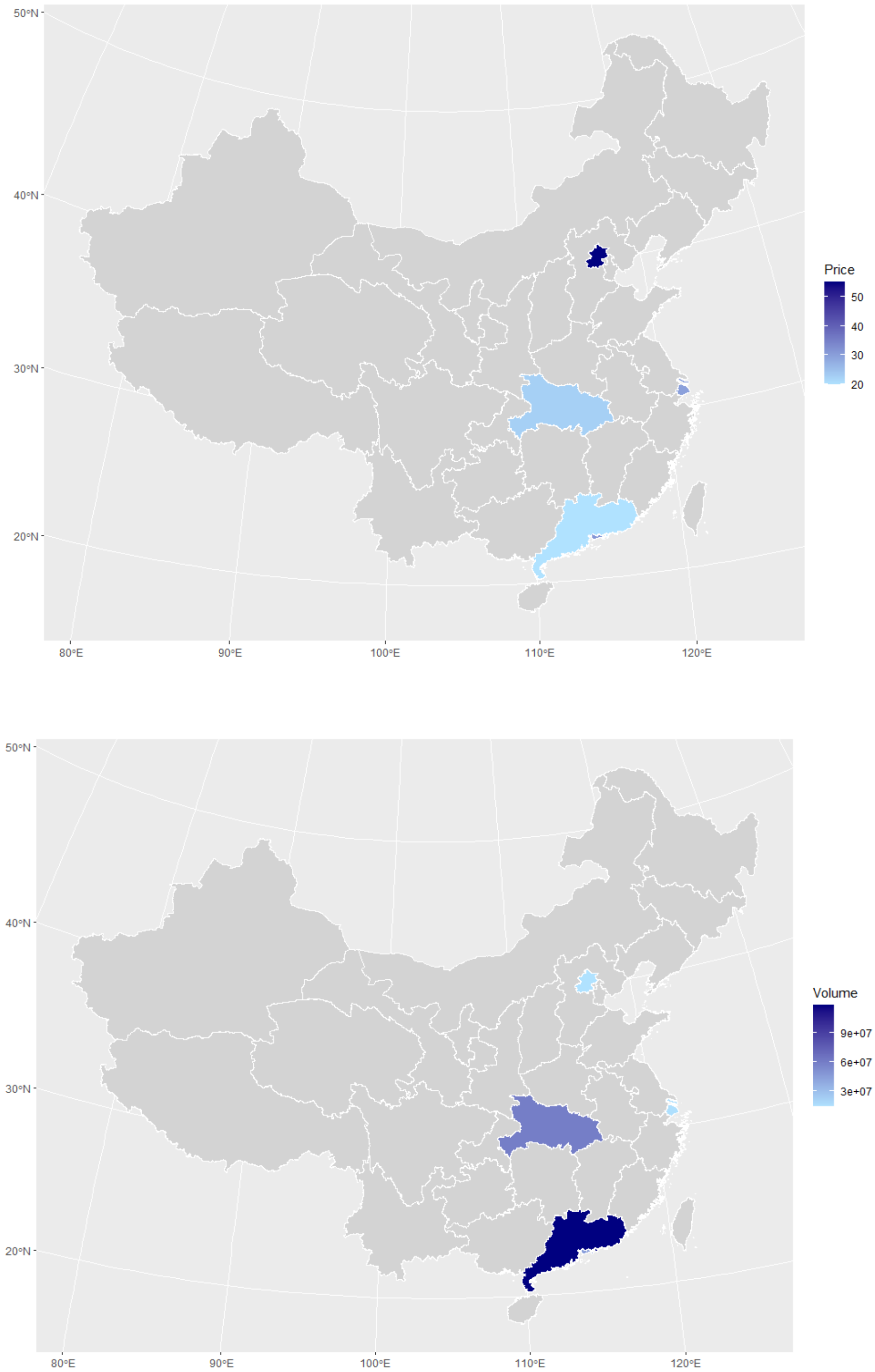
Table A2. Descriptive statistics of daily carbon spot price from seven ETS pilots

Statistic	Observation	Min	Mean	Max	Skewness	Kurtosis	St. Dev.
Beijing	776	30.3	56.8	87.5	0.90	0.12	13.5
Shanghai	730	4.2	30.6	47.8	-1.12	0.15	11.0
Guangdong	1,033	1.3	19.1	77.0	2.90	9.17	11.2
Shenzhen	1,152	3.3	30.7	77.9	0.66	1.11	13.6
Hubei	1,227	9.4	22.5	54.6	0.61	0.46	6.7

Source: Own elaboration based on data from China Beijing Green Exchange, Shanghai International Energy Exchange, China Hubei Emission Exchange, and Wind Database.

Notes: Data frequency: Daily. Price currency: Chinese yuan (RMB). Observation is the total observations. St.Dev. is standard deviation. The sample period covers from 2014-28-04 to 2019-25-12. Beijing, Shanghai, Guangdong, Shenzhen, Hubei, Tianjin, and Chongqing denote the carbon emission allowances price for Beijing ETS, Shanghai ETS, Guangdong ETS, Shenzhen ETS, Hubei ETS, Tianjin ETS, and Chongqing ETS, respectively.

Figure A1. Average price and total traded volume in five regional ETS in China



Note: BEAPrice, SHEAPrice, GDEAPrice, SZEAPrice, and HBEAPrice denote the carbon emission allowances price for Beijing ETS, Shanghai ETS, Guangdong ETS, Shenzhen ETS, and Hubei ETS, respectively.

Figure A2. ACF and PACF graphs of five regional ETSs in China

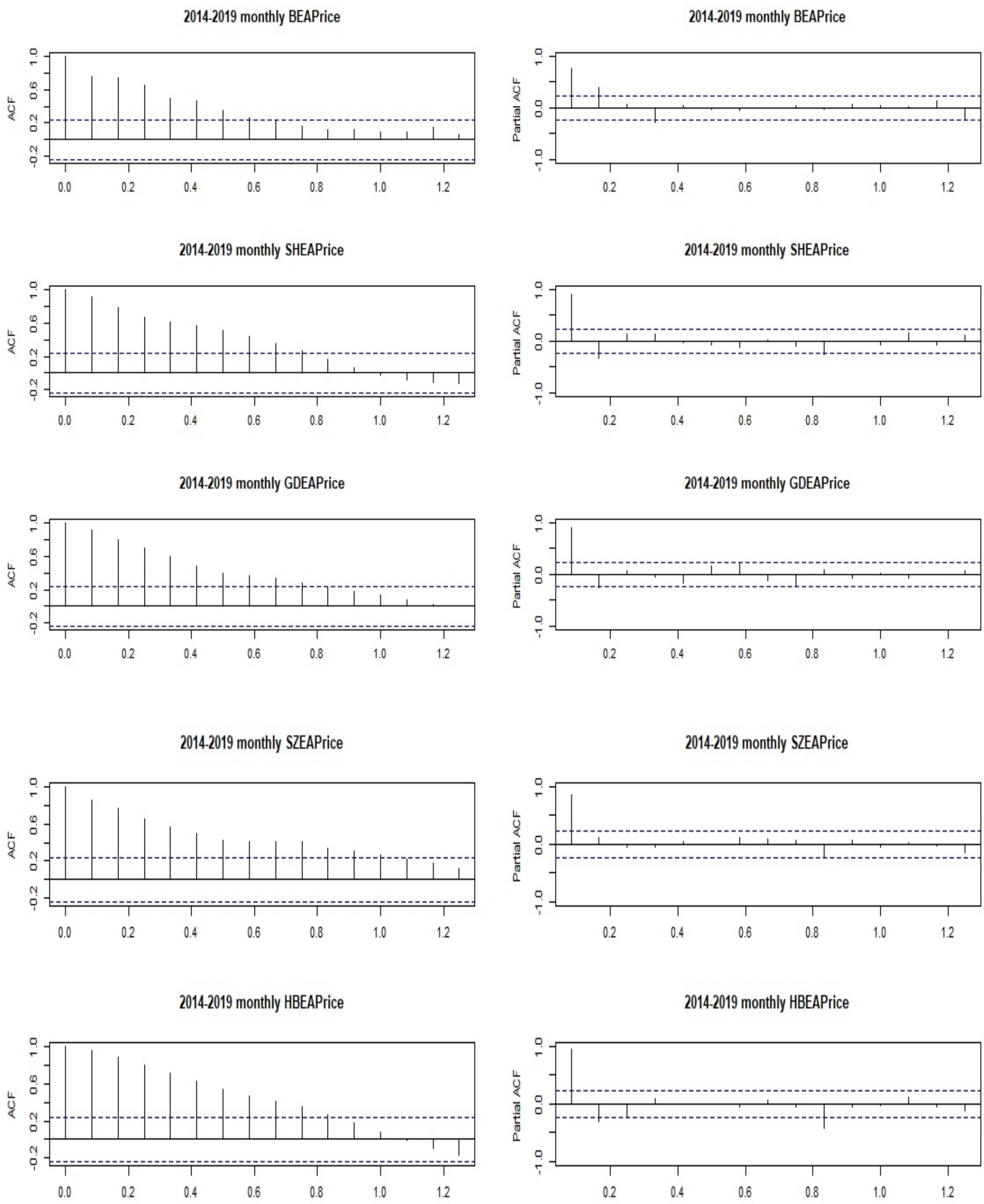


Table A3. Unit root test for carbon emission allowances price in five regional ETSs

Variables		BEAPrice	SHEAPrice	GDEAPrice	SZEAPrice	HBEAPrice
ADF	Drift	-1.6492 (AIC) Nonstationary	-2.2593 (AIC) Nonstationary	-2.596 (lag5) Nonstationary	-0.2484 (AIC) Nonstationary	-1.517 (AIC) Nonstationary
KPSS	Level	0.86*** Nonstationary	0.54** Nonstationary	0.59** Nonstationary	1.50*** Nonstationary	0.38* Nonstationary
Zivot	Trend	-3.7735 (lag1) Nonstationary	-3.8181(lag1) Nonstationary	-3.4603 (lag1) Nonstationary	-3.7018 (lag1) Nonstationary	-3.0857 (lag1) Nonstationary

(a)Unit root tests for original monthly data in level

Variables		BEAPrice	SHEAPrice	GDEAPrice	SZEAPrice	HBEAPrice
ADF	Drift	-7.9386 *** Stationary	-6.0017 *** Stationary	-6.1378 *** Stationary	-5.8979*** Stationary	-3.87*** Stationary
KPSS	Level	0.08 Stationary	0.13 Stationary	0.55 Stationary	0.13 Stationary	0.13 Stationary
Zivot	Trend	-8.6984 *** Stationary	-6.2325 *** Stationary	-8.063 *** Stationary	-6.3355 *** Stationary	-4.4091 * Stationary

(b)Unit root tests for first differenced monthly data

*Notes: All the variables are in logarithmic form and at the monthly frequency. The t-statistics are reported. *** indicates significance at the 1% level, ** indicates significance at the 5% level, * indicates significance at the 1% level. The critical values of ADF test are taken from Hamilton and Susmel (1994) and Dickey and Fuller (1981). In the Kwiatkowski–Phillips–Schmidt–Shin (KPSS) test, the null and alternative hypothesis are respectively stationary and not stationary. If type is set to "level" an intercept is added and if it is set to "trend" both an intercept and a trend are added. The critical values are taken from Kwiatkowski et al. (1992). In the Zivot - Andrews test, the null hypothesis is that the series has a unit root with structural break(s), against the alternative hypothesis that they are trend/level stationary with break(s). The critical values are taken from Zivot and Andrews (1992). Lag 1 was chosen in the Zivot test.*

Table A4. Diagnostic tests of VAR (p) specifications for five regional carbon markets

Model	**k**	**ARCH test** p value	**Serial test** p value	**JB test** p value	**Skewness** p value	**Kurtosis** p value
VAR(1)	1	0.65	0.06	< 2.2e-16	0.02831	< 2.2e-16
VAR(2)	2	0.47	0.06	< 2.2e-16	0.03	3.167e-10
VAR(3)	3	0.60	0.01	5.581e-09	0.02	1.006e-08
VAR(4)	4	0.37	0.01	1e-11	0.00	4.388e-11

Panel A. Diagnostic tests for original monthly data in level

Model	**k**	**ARCH test** p value	**Serial test** p value	**JB test** p value	**Skewness** p value	**Kurtosis** p value
VAR(1)	1	0.79	0.41	< 2.2e-16	0.01	< 2.2e-16
VAR(2)	2	0.52	0.15	3.962e-13	0.37	8.438e-15
VAR(3)	3	0.45	0.01	7.568e-11	0.10	1.487e-11
VAR(4)	4	0.55	0.02	2.851e-09	0.00	1.46e-08

Panel B. Diagnostic tests for monthly data with six dummies

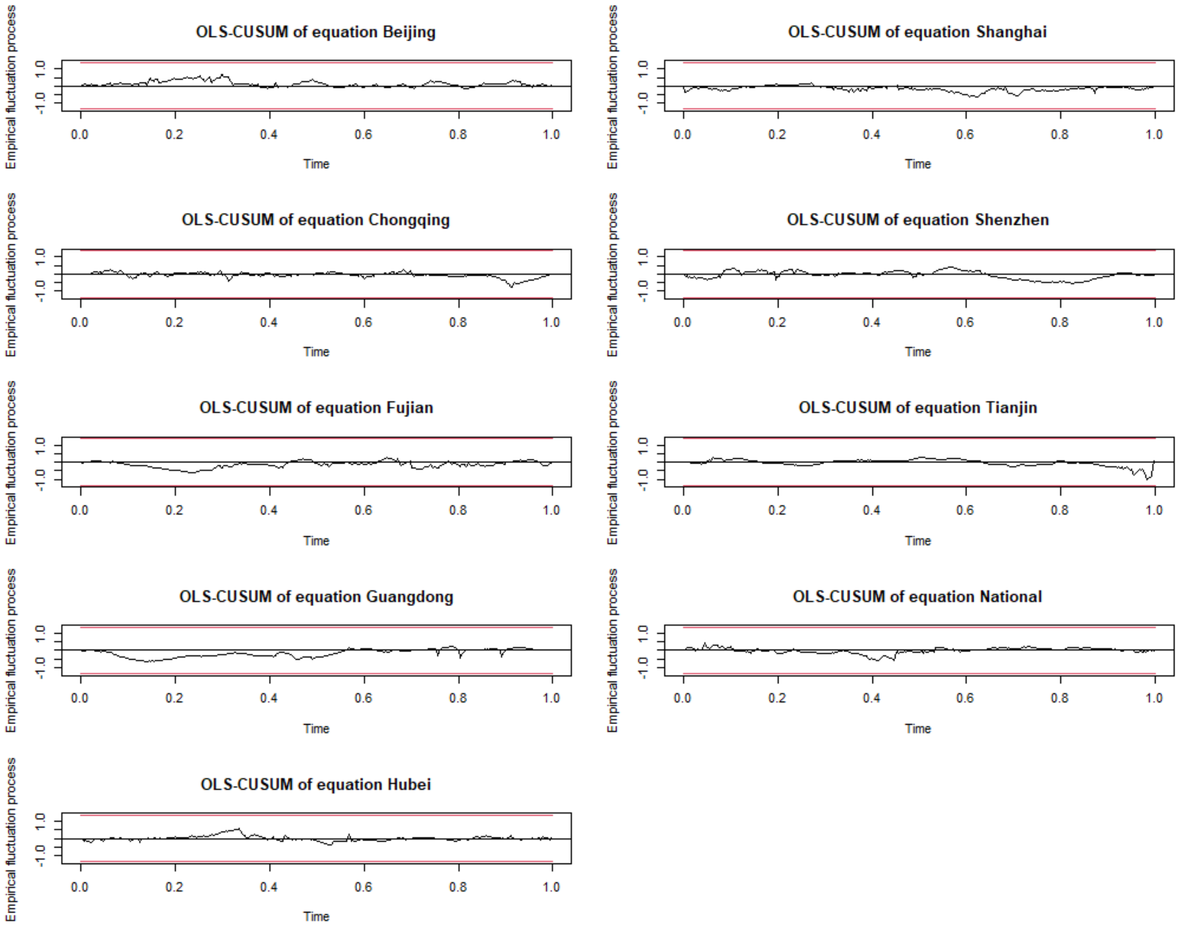
Note: The setting for the ARCH test allows multiple lag orders. JB is the Jarque-Bera test for normality of the residuals. All test statistics are asymptotically distributed as χ^2. The autocorrelation of the residuals is shown in Figure A2.

Table A5. Unit root test for carbon emission allowances price in nine regional ETSs

	Beijing	Chongqing	Fujian	Guangdong	Hubei	Shanghai	Shenzhen	Tianjin	National
ADF	-2.42	-2.16	-2.92	-1.96	-2.2	-0.62	-0.828	-0.433	0.35
KPSS	0.50***	0.55***	0.36***	0.52***	0.39***	1.03***	0.54***	0.96***	0.61***

*Notes: All the variables are in logarithmic form and at the daily frequency. The t-statistics are reported. *** indicates significance at the 1% level, ** indicates significance at the 5% level, * indicates significance at the 1% level. The critical values of ADF test are taken from Hamilton and Susmel (1994) and Dickey and Fuller (1981). In the Kwiatkowski–Phillips–Schmidt–Shin (KPSS) test, the null and alternative hypothesis are respectively stationary and not stationary. If type is set to "level" an intercept is added and if it is set to "trend" both an intercept and a trend are added. The critical values are taken from Kwiatkowski et al. (1992).*

Figure A5. Plots of structural change in VAR(4) model for China's nine ETS



Appendix B

We use the realized (historical) volatility as proxy of volatility. We can obtain only daily closing prices for the four markets; high frequency/intraday data are not available for CA CaT and HB ETS. By using the weekly highest, lowest, open, and close prices, we calculated the realized/historical volatility. To be consistent with the frequency of the historical volatility data, we use weekly returns. Three measures have been applied to estimate weekly volatility of carbon price. The first measure is the standard deviation of weekly return over the five-day interval during each week (see Equation 10 in Section 4).

The second measure is the weekly range of price that considers five prices in a week. Following Diebold and Yilmaz, (2012), and Parkinson (1980), we use weekly high and low prices obtained from daily data, from Monday open to the Friday close, to estimate weekly variance:

$$\tilde{\sigma}_{it}^2 = 0.361[\ln(P_{it}^{max}) - \ln(P_{it}^{min})]^2, \quad \text{(A1)}$$

where P_{it}^{max} is the Monday-Friday highest price, P_{it}^{min} is the Monday-Friday lowest price, $\tilde{\sigma}_{it}^2$ is an estimator of weekly variance at market i. We calculated the annualized weekly percentage volatility as $\hat{\sigma}_{it} = 100\sqrt{52\tilde{\sigma}_{it}^2}$.

The third measure is the weekly range of price that considers five prices in a week. Following Diebold and Yilmaz (2009) and Garman and Klass (1980), we use weekly high, low, opening and closing prices obtained from collected daily price data to estimate weekly carbon spot volatility:

$$\tilde{\omega}_{it}^2 = 0.511(H_t - L_t)^2 - 0.019[(C_t - O_t)(H_t + L_t - 2O_t) - 2(H_t - O_t)(L_t - O_t)] - 0.383(C_t - O_t)^2, \quad \text{(A2)}$$

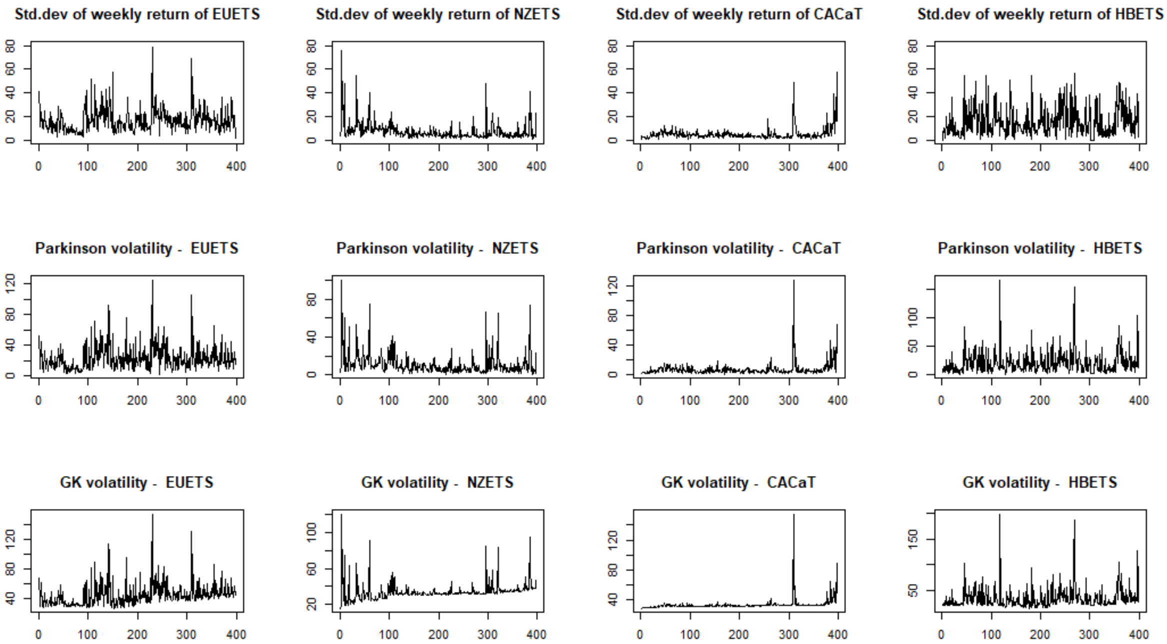
where H is the Monday-Friday highest price, L is the Monday-Friday lowest price, O is the Monday open and C is the Friday close pqrice. All prices are transformed to natural logarithms. We calculated the annualized weekly percentage volatility as $\hat{\omega}_{it} = 100\sqrt{52\tilde{\omega}_{it}^2}$. Thus, we provide the descriptive statistics for three weekly volatilities in Table A1.

Table B1. Descriptive statistics for three volatility measures – three measures of historical volatility

Statistic	EU ETS	NZ ETS	CA CaT	HB ETS
Panel A: Standard Deviation of Weekly Returns				
N	398	398	398	398
Min	1.4	0.7	0.8	0.002
Mean	16.7	7.2	4.8	15.6
Max	78.9	75.5	57.2	56.4
St.Dev.	10.1	7.5	5.3	12.5
Skewness	1.78	4.35	5.72	1.09
Kurtosis	8.62	29.79	46.14	3.56
Panel B: Parkinson (1980)				
Min	2.8	0.67	0.65	1.14
Mean	23.53	10.73	6.86	21.03
Max	125.39	100.66	127.29	166.78
St.Dev.	15.83	11.42	9.11	20.42
Skewness	1.98	3.64	7.70	2.88
Kurtosis	9.75	20.73	86.83	16.08
Panel C: Garman and Klass (1980)				
Min	26.04	15.95	28.59	15.64
Mean	43.70	34.02	33.28	34.81
Max	153.67	120.33	154.66	197.93
St.Dev.	14.86	9.66	7.97	21.04
Skewness	2.53	4.21	10.57	3.56
Kurtosis	14.42	29.29	145.33	21.62

Source: Own elaboration based on data from Bloomberg, Reuters, and Wind Database. Note: sample including carbon price volatility series from EU-ETS, NZ-ETS, CA-CaT, and HB-ETS from April 25, 2014, to December 1, 2021. The corresponding estimate of the annualized weekly volatility in percentage is $\widehat{SD}_t = 100\sqrt{52}\widetilde{SD}_t$.

Figure B1. Plots of three volatility measures – St.Dev., Parkinson, and Garman and Klass



Source: Own elaboration based on data from Bloomberg, Reuters, and Wind Database. Note: sample including carbon price volatility series from EU-ETS, NZ-ETS, CA-CaT, and HB-ETS from April 25, 2014, to December 1, 2021. The corresponding estimate of the annualized weekly volatility in percentage is $\widehat{SD}_t = 100\sqrt{52}\widehat{SD}_t$.

Figure B2. Robustness check – total connectedness index from three volatility measure

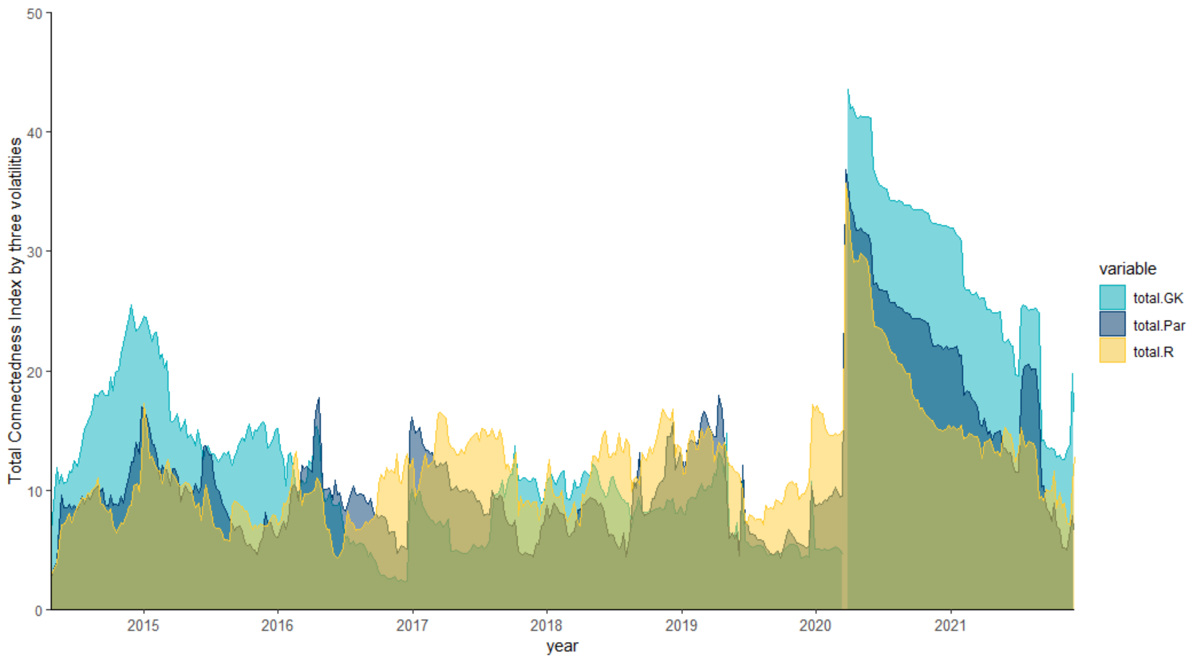
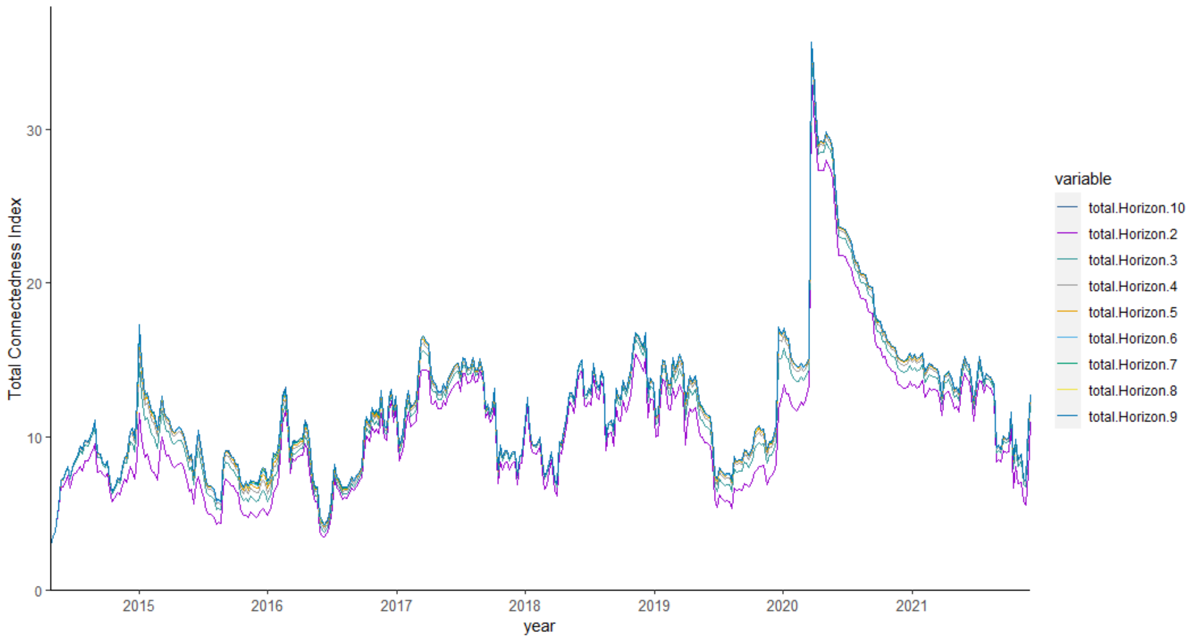


Figure B3. Sensitivity of the Total Connectedness Index to VAR lag structure

Note: The indices were calculated based on the volatilities generated with the first measure (i.e., $\widetilde{SD}_t$, from Equation 10). In the main text we used lag 1 as selected by Schwarz information criterion. Here in the robustness check we tried lag 1, lag2, and lag3 in the model (lag 3 was chosen byAkaike information criterion)

Figure B4. Sensitivity of the Total Connectedness Index to Forecast Horizon



Note: The indices were calculated based on the volatilities generated with the first measure (i.e., $\widetilde{SD}_t$, from Equation 10). We used VAR (1) for these estimations. 2 to 10-week Horizons are chosen and plotted.

Appendix C

As mentioned in Section 3.2. This study used the Primiceri (Primiceri, 2005) and Del Negro and Primiceri (Del Negro and Primiceri, 2015) prior, following Antonakakis et al. (Antonakakis et al., 2020). The mean and the variance of A_0 are chosen to be the OLS point estimates ($\hat{A}_{OLS}$) and its variance Σ_{OLS}^{A} in a time invariant VAR. Thus, the $\hat{A}_{OLS}$, Σ_{OLS}^{A}, and Σ_{OLS} are equal to the VAR estimation results of the initial subsample (first year): $A_0 \sim \mathrm{N}(\hat{A}_{OLS}, \Sigma_{OLS}^{A})$, and $\Sigma_0 = \Sigma_{OLS}$. Let $y^s = (y_1, \ldots y_s)'$ denote observations through time s. In this context filtering refers to inference on A_t through combining of the information contained in a single observation y from the equation (1) with prior information on A_t expressed through a prior distribution $\mathrm{p}(\mathrm{A}_t)$. Key steps in Kalman filtering[34] involve the result that:

$$\mathrm{A}_{t-1}|y^{t-1} \sim N(\mathrm{A}_{t-1|t-1}, V_{t-1|t-1}), \quad (3)$$

where formulae for $\mathrm{A}_{t-1|t-1}$ and $V_{t-1|t-1}$ are given in textbook sources (Koop and Korobilis, 2013). Kalman filtering then proceeds with the use of the below equation (4):

$$\mathrm{A}_t|y^{t-1} \sim N(\mathrm{A}_{t|t-1}, V_{t|t-1}), \quad (4)$$

$$\text{where } V_{t|t-1} = V_{t-1|t-1} + \Xi_t. \quad (5)$$

The prior density for $A_0|y^0$ which involves the choice of $A_{0|0}$ and $V_{0|0}$ is required for the Kalman filtering. In addition, the predictive density $\mathrm{p}(y_t|y^{t-1})$ provided by the Kalman filter can be used for forecasting y_t, given data through time t-1. Equation (5) is the only place where Ξ_t enters the Kalman filtering, and it can be removed by replacing the formulae as below:

$$V_{t|t-1} = \frac{1}{\lambda} V_{t-1|t-1}, \quad (6)$$

where λ is called a forgetting factor($0 < \lambda \leq 1$). The equation (6) implied that observations j periods in the past have weight λ^j in the filtered estimate of A_t. As we can see in equation (6), a forgetting factor approach negates the need to estimate Ξ_t. Now, to estimate the Σ_t, a similar approach involving a decay factor κ is applied. In particular, an exponentially weighted

[34] For details of Bayesian inference for A_0 involving the Kalman filter, see Frühwirth-Schnatter (Frühwirth-Schnatter, 2006).

moving average (EWMA) estimator is adopted. With the use of an EWMA estimate for Σ_t, prior information is required only for A_0:

$$A_0 \sim N(A_{0|0}, V_{0|0}).$$

$$\Xi_t = (\lambda^{-1} - 1)V_{t-1|t-1}, \quad (7)$$

$$\widehat{\Sigma_t} = \kappa\hat{\Sigma}_{t-1} + (1-\kappa)\widehat{\epsilon_t}\widehat{\epsilon_t}, \quad (8)$$

$$\Sigma_{t|t-1} = y_{t-1}V_{t|t-1}y'_{t-1} + \Sigma_t, \quad (9)$$

where $\widehat{\epsilon_t} = y_t - A_{t|t}Z_t$ is produced by the Kalman filtering method for inference on A_t. The EWMA estimators require the selection of the decay factor, κ; this study considers the benchmark values[35] for $\lambda = 0.99\ and\ \kappa = 0.96$, and keeping them constant at fixed values[36].

[35] For example, for quarterly data, $\lambda = 0.99$ implies observations five years ago receive approximately 80% as much weight as last period's observation (Koop and Korobilis, 2013).

[36] Koop and Korobilis (Koop and Korobilis, 2013) found that the value added by time-varying decay factors with respect to the forecasting performance was questionable and increased the computation burden of Kalman filter algorithm, thus, we follow Antonakakis et al. (Antonakakis et al., 2020) to keep the decay factors constant at fixed values.

Appendix D

Table A1. Descriptive statistics - Hourly price of 12 bidding areas in four countries

	Mean	Minimum	Maximum	St.Dev.	Skewness	Kurtosis	Obs.
DK1	42.00201	-200	2000	37.58594	10.3154	341.4854	107,339
DK2	44.12143	-200	2000	38.96399	8.750168	218.682	107,339
NO1	38.73736	-1.97	667.92	29.28268	3.871317	33.03959	107,339
NO2	38.26797	-1.97	667.92	28.6716	4.021594	35.54512	107,339
NO3	34.72078	-0.01	1400.11	21.38077	15.64688	770.2175	107,339
NO4	33.30415	-0.01	1400.11	21.14664	16.1768	807.6549	107,339
NO5	38.20615	-0.09	667.92	28.73403	3.929935	34.55545	107,339
SE1	35.34896	-1.97	1400.11	21.54276	15.34869	745.5188	107,339
SE2	35.35997	-1.97	1400.11	21.55098	15.33141	744.3542	107,339
SE3	39.6184	-1.97	1400.11	30.64654	8.989079	219.0297	107,339
SE4	42.12483	-1.97	1400.11	33.46208	7.729993	159.2808	107,339
FI	43.18087	-1.73	1400.11	31.45592	9.520567	228.4092	107,339

Note: Missing data exist in the original data file from Nordpool. On 28 March 2010, wholesale prices at 03:00 am were missing for all areas, resulting in a total of 13 NA existing in our sample. Since we have a large dataset, we kept 13 NAs in our hourly data.

Table A2. Correlation Test - across bidding areas in Denmark

	DK1	DK2
DK1	1	
DK2	0.834	1

Table A3. Correlation test- bidding areas in Norway

	NO1	NO2	NO3	NO4	NO5
NO1	1				
NO2	0.988	1			
NO3	0.441	0.390	1		
NO4	0.427	0.374	0.972	1	
NO5	0.989	0.994	0.403	0.388	1

Table A4. Correlation test- bidding areas in Norway

	SE1	SE2	SE3	SE4
SE1	1			
SE2	1	1		
SE3	0.697	0.697	1	
SE4	0.624	0.625	0.949	1

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