ANALYZING THE RETURN AND VOLATILITY SPILLOVERS BETWEEN GREEN BOND AND CARBON, RENEWABLE AND NON-RENEWABLE ENERGY MARKETS

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ETHICAL DECLARATION

I hereby declare that I am the sole author of this thesis and that I have conducted my work in accordance with academic rules and ethical behaviour at every stage from the planning of the thesis to its defence. I confirm that I have cited all ideas, information and findings that are not specific to my study, as required by the code of ethical behaviour, and that all statements not cited are my own.

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ABSTRACT

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Çıtak, İrem

Master's Program in Business Administration

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Due to the climate crisis concerns, energy transition and energy efficiency has emerged as a crucial field for governments, public and private organizations. To provide a sustainable and market-oriented mechanisms, the term *"green finance"* has had a flourishing interest among both scholars and practicians. Thanks to growing studies, various market-oriented instruments are emerged and implemented both developed and developing countries. One of the outcomes of green finance studies, the *"green bond"* has introduced to the market in 2007, and the market size of the green bond is growing since with the increasing awareness and interest among government, organizations and investors. Thereof, this study aims to analyze the volatility spillovers between green bond and other energy markets, namely carbon, renewable and non-renewable energy between November 7th, 2018, to November 30th, 2023, totaling a number of 1198 observations with a VAR-GARCH-BEKK approach. The empirical results indicate that there are volatility spillover effects between green bond and carbon, renewable and non-renewable energy markets.

Keywords: Green bond, carbon market, renewable energy, non – renewable energy, volatility spillovers.

ÖZET

YEŞİL TAHVİL PİYASASI İLE KARBON, YENİLENEBİLİR VE YENİLENEMEZ ENERJİ PİYASALARI ARASINDAKİ GETİRİ VE VOLATİLİTE YAYILMASI ÜZERİNE BİR İNCELEME

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İklim krizi endişeleri nedeniyle enerji dönüşümü ve enerji verimliliği hükümetler, kamu kurumları ve özel kuruluşlar için çok önemli bir alan halini almıştır. Sürdürülebilir ve piyasa odaklı mekanizmalar sağlamak için *"yeşil finansman"* terimi hem finans akademisyenleri hem de uygulayıcılar arasında artan bir ilgiye sahip olmuştur. Artan çalışmalar sayesinde hem gelişmiş hem de gelişmekte olan ülkelerde piyasaya yönelik çeşitli araçlar ortaya çıkmakta ve uygulanmaktadır. Yeşil finans çalışmalarının sonuçlarından biri olan *"yeşil tahvil"* 2007 yılında piyasaya sunulmuş olup hükümet, kuruluşlar ve yatırımcılar nezdindeki farkındalığın ve ilginin artmasıyla birlikte yeşil tahvilin pazar büyüklüğü de giderek büyümektedir. Bu nedenle bu çalışma, yeşil tahvil ile diğer enerji piyasaları (karbon, yenilenebilir ve yenilenemez enerji) arasındaki 07.11.2018 – 30.10.2023 tarihleri arasındaki volatilite yayılımını VAR-GARCH-BEKK yaklaşımıyla analiz etmeyi amaçlamaktadır. Ampirik sonuçlar, yeşil tahvil ile karbon, yenilenebilir ve yenilenemez enerji piyasaları arasında volatilite yayılma etkilerinin olduğunu göstermektedir.

Anahtar Kelimeler: Yeşil tahvil, karbon piyasası, yenilenebilir enerji, yenilenemez enerji, volatilite yayılması.

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ABBREVIATIONS

ADF: Augmented Dickey Fuller Test

APGARCH: Asymmetric General Conditional Heterogeneity

ARCH: Autoregressive Conditional Heteroscedastic

BEKK: Baba, Engel, Kraft, Kroner

CBI: Climate Bonds Initiative,

CCA: California Carbon Allowances

CCC: Constant Conditional Correlation

CO2: Carbon Dioxide

COP: Conference of Parties

DCC: Dynamic Conditional Correlation

EPU: Economic Policy Uncertainty Index

ESG: Environmental, Social and Governance.

ETS: Emissions Trading Scheme

EUA: European Union Allowances

EU ETS: European Union Emissions Trading Scheme

EUR: Euro

GARCH: Generalized Autoregressive Conditional Heteroskedasticity

GJR: Glosten, Jagannathan and Runkle

ICAP: International Carbon Action Partnership

ICMA: The International Capital Market Association

ICSS: Iterative Cumulative Sums of Squares

IEA: International Energy Agency

JB: Jarque-Bera

MGARCH: Multivariate Generalized Autoregressive Conditional Heteroskedasticity

NDC: Nationally Determined Contributions

OIX: Chicago Board Exchange Oil Index

RGGI: Regional Greenhouse Gas Initiative

SDG: Sustainable Development Goals

The UK: the United Kingdom

The US: the United States of America

TVP: Time-varying parameter

USD: the US Dollar

VAR: Vector Autoregressive

VIX: Chicago Board Options Exchange Volatility Index

CHAPTER 1: RESEARCH OVERVIEW

1.1. Research Background

Climate crisis has emerged as a critical worldwide policy domain for governments, posing the challenge of ecological sustainability while safeguarding economic growth (Gilchrist et al., 2021; Bolton et al., 2020; Trippel, 2020). Several international efforts, such as Kyoto Protocol, the Paris Agreement (Nationally Determined Contributions *"NDC"*), and the Sustainable Development Goals *"SDGs"*, have been established to address this challenge. The Glosgow Climate Pact (COP26) also aims to decrease CO2 and pacing the transition toward net zero emissions by 2050. These efforts have resulted in an increased demand for clean energy, and it is projected that 40% of energy consumption will come from clean sources by 2040 (Tariq et al., 2023; Tolliver et al., 2020.

Although the global economy was severely shaken by the Covid-19 pandemic, which led to an unparalleled 5.8% decrease in CO2 emissions in 2020, CO2 emissions related to energy began to rise globally once more in December 2020 (IEA, 2021a). The developing countries has faced more with the damaging effects of Covid-19 as the economic downturn is more profound, and sustainable recovery is more challenging (IEA, 2021b). Furthermore, The Russia occupation of Ukraine raised energy security concerns more substantial on the European economy's agenda and the crisis has triggered the urgency of European Green Deal targets of being more resilient and less dependent on imported energy via promoting renewable energy and energy efficiency (ICAP, 2023).

Carbon markets, as a crucial pillar of climate change combat, have been widely accepted by the market actors and demonstrated massive development since their potential for creating new cycles of investment, profitability, and growth (Paterson, 2012). The carbon market and the emissions trading schemes *"ETS"* are frequently interconnected whereas carbon tax is another method that should be mentioned and targets reducing greenhouse gas emissions via direct pricing. Carbon emission trading allows emitters to meet their emission targets by trading emission rights at the market which carbon price is determined in accordance with supply and demand principle. The system is derived by the Coase's theorem, which states that as the property rights explicit, the market can solve externalities without direct government actions (Ji et al., 2018). The World Bank reported that in 2023, ETS or carbon tax encompasses 23% of the global greenhouse gas emissions. Although mainly dominated by high-income countries, emerging countries such as Chile, Malaysia, Vietnam, Thailand, and Turkey have also put effort by initiating carbon pricing (World Bank, 2023).

Over and above that, it is expected that by early 2025, renewable energy will replace coal as the world's main electricity source. Furthermore, IEA projects that in 2027, the renewable energy share of the overall power mix will reach 38% with an increase of 10%. In the next five years, the amount of electricity generated by wind and solar PV will increase by over twofold and account for nearly 20% of worldwide power generation (IEA, 2022). Nonetheless, non-renewable energy sources continue to meet a sizable amount of global energy demand and are recognized as the main industries among the energy stock markets, since mostly economies have a substantial dependence to fossil fuels (Hu et al., 2022; He et al., 2023).

Brought at the stake by mentioned developments, the understanding of *"green finance"* refers to a broad category of financial investments committed to environmental goods, legislation, and initiatives that support sustainable development and it includes the climate finance whereas not limited to it (Höhne et al., 2012). The funding of public policies, the issuance of effective instruments, and the funding of private and public environmental investments are all included in the category of "*green finance*".

Within this scope, the green bond is a type of green finance instrument that gives investors fixed or recurring income payments while funding green projects. As a crucial component of the green financial market, it functions as a direct source of funding for eco-conscious projects and promotes the growth of the carbon-free, sustainable economy (Zheng et al., 2023). The International Capital Market Association (ICMA) identifies green bond as any type of bond instrument in which the proceeds, or a corresponding amount, will only be used to finance eligible new and/or existing green projects partially or fully. Ecologically sustainable land use and resource management, renewable energy, energy efficiency, pollution prevention and control, clean logistics are a few examples of eligible green projects (ICMA, 2021).

Since presented by European Investment Band in 2007, environmentally responsible investors are interested in green bonds due to its feature of being an alternative fixed-income asset, its climate change combat function as well as the providing opportunity for diversifying portfolio and managing risks (Tiwari et al., 2022).

The volume of aligned green bonds has reached USD278.8bn at the first half of 2023, with a 33% increase compared to second half of 2022. Supported by sovereign issuance, aligned green bonds with a minimum volume of USD50 billion were priced in March and April, reaching a peak of USD52 billion in May. In fact, compared to their equivalents, green bonds in the EUR and USD saw higher spread compression and book cover during the first half of 2023 (CBI, 2023).

1.2.Goals of the Research and Research Questions

Under the given market conditions, due to its growing potential and popularity, it is worthwhile to consider if green bonds might serve as a hedging asset for energy portfolios during the energy transition process. Thus, our study aims to investigate the volatility spillovers between green bond, carbon market, renewable and non-renewable energy markets so that suggesting investors and corporations a well-balanced portfolio, also certain energy finance policies for governments by assessing the hedging and diversification effects of green bond.

Given the scarcity of research on green bonds, there is growing interest in investigating the relationship between green bonds and other types of renewable and non-renewable energy stocks, as well as the role of the carbon market in this relationship. Therefore, this study aims to fill this gap in the literature by including comprehensive analysis of the spillover effects among green bond, carbon market, renewable and non-renewable energy stocks using a most up-to-date dataset.

This thesis contributes to empirical literature in three aspects. First of all, it offers a unique contribution to literature by being the first study to investigate the return and volatility spillover effects among green bond, carbon market, renewable and non-renewable energy stocks. Furthermore, this study provides new evidence by analyzing the volatility effects among these markets by using MGARCH with BEKK model established by Engle and Kroner (1995), as it is accepted as one of the most convenient models for the inspection of volatility spillover studies since it defines the positive definite covariance matrix. The BEKK alteration of MGARCH model is noteworthy for not placing any limitations on the correlation structure among the variables. Furthermore, this study also aims to provide policy implications regarding portfolio building for investors and corporations and certain energy finance policies for governments.

Considering sustainable finance instruments, such as green bons, the results attract investors as well as corporations with concrete portfolio recommendations so that the usage and issuance of green bond instruments could be broadened.

Through the research, the following questions are aimed to be answered.

- *Are there any volatility spillover effects between green bond, renewable and non-renewable energy and carbon markets?*
- *Do green bond act as hedging tool for price fluctuations in renewable energy, non-renewable energy and carbon markets?*

1.3. Hypothesis Development

For the purposes of this study, 3 hypotheses are developed based on the research questions as followed.

- ***H1.*** There exist volatility spillover effects among green bond, carbon, renewable and non-renewable energy markets.
- ***H2.*** Green bond does act as a hedging tool for price fluctuations carbon, renewable, and non-renewable markets.

CHAPTER 2: LITERATURE REVIEW

The literature on green bond is growing, yet it is generally policy oriented. Tolliver et al. (2020) concluded that Nationally Determined Contributions *"NDCs"* have immense effects on the green bonds for renewable energy. MacAskill et al. (2021) highlighted that strengthening the environmental preferences among market participants is crucial for green bond market.

From the policy perspective of green bonds, the barriers for a well-functioning green bond market are studied immensely among scholars. Jun et al. (2016) defined several such as;

> *"General obstacles to the development of the bond market"*, *"the absence of knowledge about the advantages, current international standards, and guidelines"*, "*the absence of local guidelines"*.

Lee et al. (2023) revealed that green bond policies proactively promote green innovation, and these policies have the same effect for different cities worldwide.

Despite the flourishing interest among investors, the finance literature regarding green bonds is still limited. The current finance literature is mainly focused on comparison of green bond with conventional bonds, the co-movement and volatility spillovers between green bond and other markets. The co-movement between carbon market and other energy markets are also immensely investigated. Although there are many studies examining the relationship between renewable and non-renewable markets, the interest among scholars is decreasing, a reason may be establishment of new market instruments.

2.1. Green Bond – Conventional Bond Nexus

In comparison to traditional bonds, the procedure for issuing green bonds is more stringent. In their study, Hachenberg and Schiereck (2018) compared green bonds to traditional bonds and discovered that green bonds have lower rated issuers and larger issue sizes.

There are many studies highlighting that the risk of green bonds is lower compared to conventional bonds, indicating a green premium or *"greenium."*- which is a term identified as the yield difference of green bond, comparing to its identical traditional bond. Karpf and Mandel (2017) compared the green bonds to *"brown bonds"* and found that green bonds are traded at lower prices/higher yields than expected comparing to their credit profile.

Zerbib (2019) investigated how pro-environmental preferences affect the prices by comparing green bond and its identical traditional bond issued by same corporations to eliminate the other factors and concluded that the yield on a green bond is lower than of its identical traditional bond.

Barua and Chiesa (2018) mentioned that the volume of green bonds and the coupon rate are adversely correlated. Furthermore, in search for the relationship between the green and conventional bond markets, Cheng (2019) discovered that a number of macroeconomic factors such as

> *"financial market volatility, the uncertainty surrounding economic policy, and daily economic activity in the US capital market"*

have an impact on the relationship between these two.

Li et al. (2021) discovered that there is a bidirectional spillover effect between the green bond and conventional bond, and green bond is a spillover receiver from stock and commodities markets. Elsayed et al. (2022) also studied the connectedness among green bond and financial markets and concluded that green bond is a volatility receiver, yet not a transmitter.

Febi et al. (2018) examined how liquidity premiums affect green bond market by considering credit risk, bond-specific and macroeconomic factors and found that they have a positive correlation, also in general, the liquidity of green bonds are more than conventional bonds. Tang and Zhang (2019) studied announcement returns and real effects of green bond issuance and concluded that issuance of green bond increases the stock liquidity and provides shareholders benefits.

Bachelet et al. (2019) analyzed the characteristics of green bond and conventional bonds and revealed that the liquidity and yield of green bond are higher, yet its' variance is lower, highlighting the differentiations arising from issuers. Flammer (2020) studied corporate green bonds and found that investors respond favorably to the announcement of issuance, and this response is stronger for bonds certified by third parties and for bonds issued by first-time issuers. Lebelle et al. (2020) proved that the investors' perception is equivalent as it is for conventional / convertible bonds.

Reboredo (2018) demonstrated that green bonds have a high diversification effect in the US and the EU, in contrast to corporate and treasury bonds, which have low transmission shocks from green bonds to other bonds. Likewise, Reboredo et al.'s (2020) study, which also examined the relationship between green bonds and conventional assets, found that while there is a limited relationship with high-yield corporate bonds, there is a significant correlation and spillover effects between green bonds and government and corporate bonds.

Furthermore, Pham (2016) discovered volatility clustering in these markets when examining the tail dependence between conventional bonds and green bonds.

2.2. Green Bond – Energy Markets Nexus

Pham and Nguyen (2022) analyzed the effects of economic policy and financial market uncertainty on green bond returns via using stock volatility (VIX), oil volatility (OIX) and EPU indices and discovered that uncertainties vary over time and the state factor is also substantial, yet connectedness increases during times of crisis. Chousa et al. (2021) demonstrated that stock market (VIX) does not have an influence on green bond market. Tolliver et al. (2020) showed that economic progress has a significant effect on green bond market development, while the institutional framework has an indirect effect on green bond market.

Liu et al. (2020) demonstrated a positive time-varying average and also the tail dependence between the green bond and clean energy markets, and their study also proved the spillover effect between the two markets. Naeem et. al (2021) highlighted that green bond may have hedging effects against natural gas, certain industrial and agricultural products.

Tiwari et al. (2022) showed that green bonds receive the shocks of other green energy indices in both the short and long run. This founding is approved by Dwumfour et al. (2022) with a TVP-VAR method.

Jin et al. (2020) studied the hedging effect of green bond against carbon market risk by DCC-APGARCH, DCC-T-GARCH, DCC-GJR-GARCH, constant hedge ratio

(OLS) model. They discovered that the carbon market has the strongest correlation with the green bond index.

Yin et al. (2023) studied the time varying spillovers between carbon emission stocks, green bond and crude oil and find that found that while the tail is less volatile, the connectivity is time-varying in every scenario.

2.3. Carbon – Energy Markets Nexus

Primitive studies highlighted that carbon market relates to energy prices. This finding is approved by the studies of Kim et al. (2010), Zeng et al. (2017), Zhao et al. (2018) and Jiang et al. (2018). Jiang (2018) especially highlighted the negative correlation between the coal and carbon price with a dynamic view.

Wang and Guo (2018) proved magnitude spillover effects from oil and natural gas to EU ETS market. Marimoutou and Soury (2015) studied on the Phases II and III of European Emissions Trading Scheme and found that prices and volatility of carbon and energy returns, coal, natural gas, Brent oil prices are connected, and this connection becomes stronger during crisis times. Tan and Wang (2017) found that the volatility of oil price in Phase II, and coal price in the Phase III enlarged the risk of EU ETS market. Wu et al. (2022) studied the dynamic frequency spillovers between ETS, fossil and sectoral stock markets in China market, and found that the spillover between carbon and fossil market is mainly negative, yet the spillover to carbon market from natural gas is greater comparing to coal.

Constantinos et al. (2019) examined the intertemporal causal relationship between crude oil and carbon emissions and found asymmetrical correlation in the long run from each direction, yet asymmetric effects solely exist from carbon to crude oil prices in the short run. Yu et al. (2015) studied volatility spillover between carbon and crude oil market via Dynamic Conditional Correlation (DCC) model and Iterative Cumulative Sums of Squares (ICSS) model and highlighted a positive spillover between ETS and Brent market, yet the dynamic spillover is getting less substantial in Phase III comparing to Phase II.

The spillover effect of renewable market as receiver from carbon market is firstly suggested by Kumer et al. (2012). Later on, Koch et al. (2014) and Dutta et al. (2018)

examined the return and volatility linkage between carbon and renewable energy market.

2.4. Renewable - Non-Renewable Energy Markets Nexus

Asl et al. (2021) analyzed the return and volatility effects between clean energy, natural gas and crude oil and concluded that the positive return on renewable energy stocks more than offsets the adverse return on natural gas and crude oil, therefore, these stocks have hedging effects on each other. Ferrer et al. (2018) also studied the frequency and time dynamics of connectivity between crude oil and US clean energy companies' stock prices, and the results demonstrated a robust connectivity in very short-run, yet the relativity become weaker in the long-run. Henriques and Sadorsky (2008) also concluded that crude oil prices barely affect the renewable energy stocks via VAR analysis. In contrast, Reboredo (2015) found that there is a symmetrical pattern between crude oil and renewable energy stocks via CoVar approach.

Ahmad et al. (2018) investigated the viability of hedging a clean energy equity investment using gold, bonds, oil, VIX, OVX and European carbon prices via three distinct MGARCH variants and found that the most effective instrument for hedging clean energy stocks is VIX. Lundgren et al. (2018) studied the interconnectedness and directionality between renewable energy stock returns and certain assets stocks, currency, US Treasury bonds, oil, also considering the uncertainty impact.

On the other hand, Uddin et al. (2019) studied the cross-quantile reliance between renewable energy stock and the overall stock returns, price fluctuations in gold and oil, and exchange rates. They concluded that there is an asymmetry in the relationship among oil and renewable energy throughout the quantiles, the degree of asymmetry getting stronger at longer lags.

CHAPTER 3: METHODOLOGY

This thesis endeavors to assess causality and volatility spillovers through the utilization of Granger Causality and Multivariate Generalized Autoregressive Conditional Heteroskedasticity (GARCH) models. Preceding the application of these methodologies, the stationarity of the variables is examined through Augmented Dickey-Fuller (ADF) Unit Root Test. Subsequently, an ARCH Lagrange Multiplier test is employed to identify Autoregressive Conditional Heteroskedasticity (ARCH) effects within the variables.

3.1. Unit Root Tests

Most of the time, economic time series seem to demonstrate nonstationary characteristics. Some series may have no fixed population mean, whereas others demonstrate secular patterns over long periods of time. This necessitates an introduction of a method that captures the nonstationary elements in the series or adjusts the non-stationary series to carry stationary characteristics (Phillips, 1998).

3.1.1. The Dickey – Fuller Test

The Dickey – Fuller tests the autoregressive moving average (ARIMA) null hypothesis against stationary and alternatively.

Assume an AR (1) model:

$$Y_t = \rho\, Y_{t-1} + \varepsilon \qquad (1)$$

Dickey – Fuller model subtracts Y_{t-1} from both sides of the equation (1)

$$Y_t - Y_{t-1} = \rho\, Y_{t-1} - Y_{t-1} + \varepsilon$$

$$\Delta\, Y_t = (\rho\text{-}1)\, Y_{t-1} + \varepsilon$$

$$\Delta\, Y_t = \Upsilon\, Y_{t-1} + \varepsilon \qquad (2)$$

Two alternatives of the Dickey – Fuller are as follows:

Constant only:

$$\Delta\, Y_t = \alpha + \Upsilon\, Y_{t-1} + \varepsilon \qquad (3)$$

Constant and time trend:

$\Delta Y_t = \alpha + \beta_t + \Upsilon Y_{t-1} + \varepsilon$ (4)

3.1.2. Augmented Dickey – Fuller (ADF) Test

The Augmented Dickey – Fuller (ADF) test is mostly preferred rather than simple Dickey – Fuller test. ADF test includes the lagged values of dependent variables to the Dickey – Fuller test until the autocorrelation is eliminated. It can be demonstrated as:

$Y_t = \beta_1 + \beta_2 Y_t + \varepsilon_t$ (5)

$Y_t = \beta_1 + \beta_2 Y_t + \beta_3 Y_{t-1} + \varepsilon_t$ (6)

$Y_t = \beta_1 + \beta_2 Y_t + \beta_3 Y_{t-1} + \beta_4 Y_{t-2} + \varepsilon_t$ (7)

$\Delta Y_t = \Upsilon Y_{t-1} + \beta_1 \Delta Y_{t-1} + \varepsilon_t$ (8)

$\Delta Y_t = \Upsilon Y_{t-1} + \beta_1 \Delta Y_{t-1} + \beta_2 \Delta Y_{t-2} \ldots\ldots\ldots\ldots\ldots + \beta_p \Delta Y_{t-p} + \varepsilon_t$ (9)

The model (9) can be expressed as:

$\Delta Y_t = \Upsilon Y_{t-1} + \sum_{i=1}^{p} \beta_1 \Delta Y_{t-1} + \varepsilon_t$ (10.1)

$\Delta Y_t = \alpha + \Upsilon Y_{t-1} + \sum_{i=1}^{p} \beta 1 \Delta Y_{t-1} + \varepsilon_t$ (10.2)

$\Delta Y_t = \alpha + \beta_t + \Upsilon Y_{t-1} + \sum_{i=1}^{p} \beta 1 \Delta Y_{t-1} + \varepsilon_t$ (10.3)

3.2. VAR Model

Since Sims's study in 1980, the vector autoregression (VAR) model has gained popularity as one of the most practical and successful methods for analyzing multivariate time series. It is commonly acknowledged that the VAR model is particularly helpful for forecasting and characterizing the dynamic behavior of financial and economic time series. When it comes to explaining and predicting the dynamic behavior of financial and economic time series, the VAR model is especially helpful (Zivot et al., 2003).

Assuming $Y_t = (y_{1t}, y_{2t}, \ldots y_{nt})'$ represents a $(n \times 1)$ vector of time series variables, the simple autoregressive VAR(p) model can be described as:

$Y_t = c + \Pi_1 Y_{t-1} + \Pi_2 Y_{t-2} + \ldots + \Pi_p Y_{t-p} + \varepsilon_t,\ t = 1, \ldots, T$ (11)

where:

Π_2 are *(n x n)* coefficient matrices and ε_t is an *(n x 1)* unobservable zero mean white noise vector process with time invariant covariance matrix, $\sum$.

3.3. ARCH/GARCH Models

The ARCH/GARCH models are particularly useful when analyzing time series data and are preferred by academics for volatility spillover studies. The least squares models essentially assume that at any given point, the squared expected value of all error terms is the same. The foundation of ARCH/GARCH models is this assumption, known as homoskedasticity. On the contrary, heteroskedasticity refers to data where the error terms' variances are not equal and where it is reasonable to anticipate that the error terms will be larger for some data points or ranges than for others. The fact that the model views heteroskedasticity as a variance to be modelled rather than an issue to be fixed, is one of the key characteristics that distinguishes the futures of the GARCH and ARCH models. As a result, each error term's predicted variance is computed in addition to the least squares errors being corrected (Engle).

3.3.1. ARCH LM Test

Engle's (1982) ARCH – LM test is the standard method for detecting autoregressive conditional heteroscedasticity. As can be defined in variety of context regarding the stochastic linear regression model's error distribution, the ARCH process can be defined as:

If y_t is assumed to be generated by

$$y_t = x_{t-1}\xi + \varepsilon_t,\ t = 1,...,T \tag{12.1}$$

where x_t represents extrinsic variables and ξ represents regression parameters in $k \times 1$ vector. The ARCH model defines the distribution of the dynamic error ε_t conditional on the realized values of the set of variables $\Psi_{t-1} = \{y_{t-1}, x_{t-1}, y_{t-2}, x_{t-2},...\}$ [Bera et al. (1993)].

The original Engle's (1982) ARCH model assumes:

$$\varepsilon_t \mid \Psi_{t-1} \sim N(0, h_t) \tag{12.2}$$

where $h_t = \alpha_0 + \alpha_1\, \varepsilon^2_{t-1} + \ldots\ \alpha_q\, \varepsilon^2_{t-q},$

(12.3)

with $\alpha_0 > 0,\ a_i \geq 0\ ,\ i = 1,\ldots q$

Subsequently, for the large *q*, the conditional variance is developed by Engle (1982, 1983) as:

$$h_t = \alpha_0 + \alpha_1 \sum_{i=1}^{q} \omega_i\, \varepsilon^2_{t-i}, \tag{12.4}$$

where the weights:

$$\omega_i = \frac{(q+1)-i}{\frac{1}{2} q\ (q+1)} \tag{12.5}$$

3.3.2. Single – Dimensional GARCH Model

An extended version of the conditional variance function (11.3) is developed by Bollerslev (1982) and termed as generalized ARCH (GARCH).

The model defines the conditional variance as:

$$h_t = \alpha_0 + \alpha_1\, \varepsilon^2_{t-1} + \ldots + \alpha_q\, \varepsilon^2_{t-q} + \beta_1 h_{t-1} + \ldots + \beta_p h_{t-p} \tag{13}$$

where:

$\alpha_0 > 0$

$\alpha_i \geq 0 \text{ for } i = 1,\ldots,q$

$\beta i \geq 0 \text{ for } i = 1,\ldots,p$

Thereof the full Bollerslev's GARCH model can be described as:

$$h^2_t = \omega + \sum_{i=1}^{q} \alpha_i\, \varepsilon^2_{t-i} + \sum_{j=1}^{p} \beta_j h^2_{t-j} \tag{13.1}$$

3.3.3. Multivariate GARCH Models

Multivariate GARCH models (MGARCH) are the extended versions of the GARCH model. The models can be grouped as;

Models of conditional covariance matrices: This group refers to models that are built with the large of parameters. *i.e.* VEC model of Bollerslev et al. (1988), BEKK model of Baba et al. (1993).

Models of correlations and conditional correlations: In this group of models, the variance and correlation matrix are utilized for estimating the conditional correlation matrix. *i.e.* Constant Conditional Correlation (CCC) model, the Dynamic Conditional Correlation (DCC) model.

Factor models: This group of models is based on the assumption that the rationale behind the returns is certain heteroskedastic unobservable factors [Silvennoinen and Terasvirta (2008)].

Semi parametric and non-parametric models: The identifying feature of these models is not imposing either distribution or structure on the data, thereof misspecification issues are eliminated [Silvennoinen and Terasvirta (2008)].

3.3.3.1 GARCH – BEKK Model

Due to the limits on the linear operators, the introduction of BEKK model developed by Baba et al. (1993) became inevitable to ensure the positive semi definiteness [Stelzer (2008)]. For the full BEKK model, the conditional covariance equation is as follows:

$$H_t = C_0 C^T_0 + \sum_{q=1}^{Q} . \sum_{i=1}^{l} A_{qi}\, \varepsilon_{t-i}\, \varepsilon^T_{t-i}\, A^T_{qi} + \sum_{q=1}^{Q} . \sum_{j=1}^{m} B_{qj}\, H_{t-j} B^T_{qj} \qquad (14)$$

where A_{qi}, B_{qi} and C_o are $p\ x\ p$ parameter matrices and C^0 is lower triangular. The parameter Q in the model enables more flexible representations of conditional covariance equations (Livingston et al., 2023).

For the purposes of this study the model is defined as follows:

$$h_{12,t} = c_{11}c_{21} + a_{11}a_{12}\varepsilon^2_{1,t-1} + (a_{21}a_{12} + a_{11}a_{22})\varepsilon_{1,t-1}\varepsilon_{2,t-1} + a_{21}a_{22}\varepsilon^2_{2,t-1} + b_{11}b_{12}h_{11,t-1} + (b_{21}b_{12} + b_{11}b_{22}) + h_{12,t-1} + b_{11}b_{22}h_{22,t-1}$$

- *($h_{12,t}$), the conditional covariance, captures the relationship between green bond and other markets, carbon, renewable, nonrenewable energy markets.*
- *a_{11}, a_{22}, ARCH parameters, measure the effect of a previous shock on the volatility of the same variable.*
- *b_{11}, b_{22}, GARCH parameters, measure the degree of volatility persistence.*

- *The off-diagonal elements in matrices A, (a_{12}, a_{21}), capture the cross-market shock effects and while the elements in matrices B, (b_{12}, b_{21}), measure the volatility spillovers effects among the markets.*

CHAPTER 4: DATA AND SUMMARY STATISTICS

4.1. Data Description

The main variable considered in this study is the Solactive Green Bond Index that includes green bonds issued by central governments, government-related and corporate issuers. The index is rules-based, and market value weighted. The other variables include IHS Markit Global Carbon Index, EQM Solar Energy Index, S&P Global Clean Index, ICE Europe Rotterdam Coal Future, ICE UK NBP Natural Gas Future Index. The index for solar energy is solely examined due to its feature of being the main renewable energy source, whereas other renewables such as wind, hydro, biomass are represented by S&P Global Clean Index as mentioned in Section 4.1.3 and Section 4.1.4.

For the purposes of this study, the hedging effect of the green bonds against carbon, renewable and non-renewable market volatilities is examined using daily data spanning from over the period November 7th, 2018, to November 30th, 2023, totaling a number of 1198 observations. All data is obtained from Thomson Reuters DataStream.

Table 1. Descriptions of markets and market stock indices

Market	**Index**
Green Bond	Solactive Green Bond Index (SOLGREEN)
Carbon	IHS Markit Global Carbon Index (GLCARB)
Solar	EQM Solar Energy Index (SOLARNTR)
Other Renewables	S&P Global Clean Index (SPGTCLEN)
Coal	ICE Europe Rotterdam Coal Future Index (ARA)
Natural Gas	ICE UK NBP Natural Gas Future Index (NBP)

4.1.1. Solactive Green Bond Index as a Proxy for Green Bond (SOLGREEN)

Index components are weighted based on their market values, which are compared to the total market values of all index components in the index. The maximum weight for each bond is 5%. In other words, the cap of 5% per bond does not apply if the index consists of fewer than 20 bonds. The largest group in the index is financial corporates, with an issue volume of USD 81 billion in 2020. According to latest data, financials had a weight of 39.5% as of the end of June 2021, when the index's most recent composition was determined based on outstanding market value.

As described in Figure 1, green bond returns have smooth fluctuations until recent years, yet a dip and volatile increasing trend are observed afterwards.

Figure 1. Time variations of Solactive Green Bond Index

4.1.2. IHS Markit Global Carbon Index as a Proxy for Carbon Market (GLCARB)

The index monitors the most actively traded carbon credit futures contracts by providing a wide range of cap-and-trade carbon allowances. The index includes the key cap-and-trade systems of Europe and North America, namely EUA, CCA and RGGI.

Figure 2 demonstrates that carbon returns have generally an increasing trend throughout the years and fluctuations have become less dramatic recently.

Figure 2. Time variations of IHS Markit Global Carbon Index

4.1.3. EQM Solar Energy Index as a Proxy for Solar Energy (SOLARNTR)

The index is the representation of securities with primary business focus on the solar energy industry. Companies with over 60% of their revenue coming from solar-related operations are deemed core constituents and obtain a score of 1.0. Companies with at least 5% and up to 60% of their revenue coming from solar business operations are rated as non-core elements and obtain a score of 0.5. The weights of the index components are the same for these two categories.

In the Figure 3, a sharp increase and then smoother fluctuations are shown in solar energy returns, most recently a considerable dip is observed.

Figure 3. Time variations of EQM Solar Energy Index

4.1.4. S&P Global Clean Index as a Proxy for Clean Energy (SPGTCLEN)

The index's objective is to assess the effectiveness of international clean energy companies operating in both developed and developing nations. It consists of businesses that produce energy from renewable sources, as well as those that develop and supply clean technology. The index is run according to the mentioned principles: it targets a constituent count of 100, weights constituents according to the product of market capitalization and exposure score, chooses companies based on clean energy exposure score and market capitalization, without going over a dilution threshold (0.85), and assigns energy exposure scores to companies. It also applies business activity standards and ESG screenings, removing businesses with comparatively high carbon footprints.

Just like the Figure 3, Figure 4 demonstrates a sharp increase and then smoother fluctuations with a recent dip.

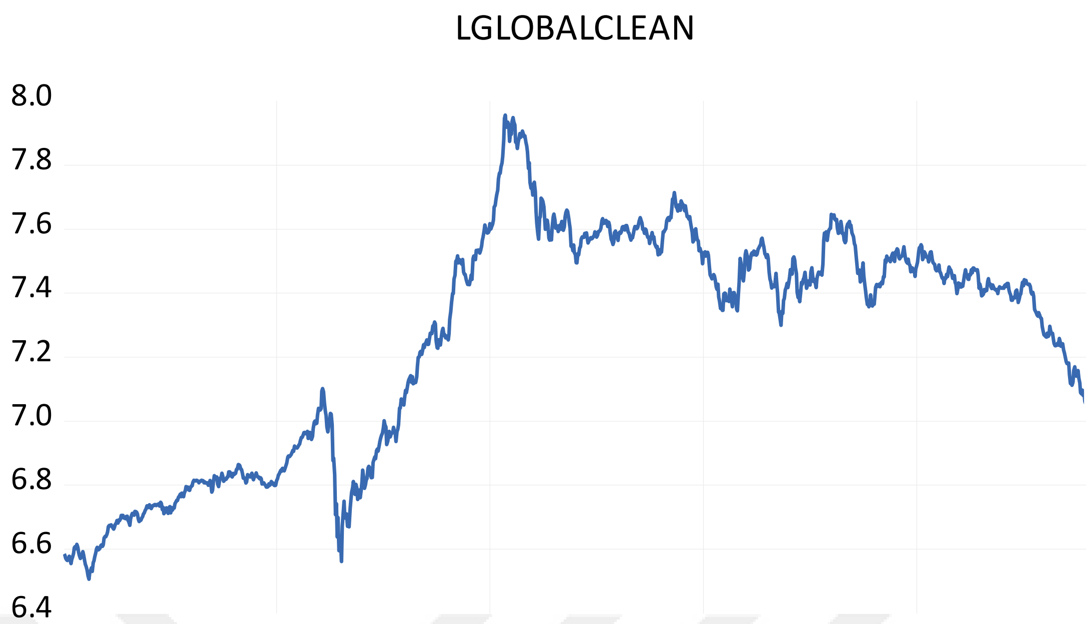

Figure 4. Time variations of S&P Global Clean Index

4.1.5. ICE Europe Rotterdam Coal Future Index as a Proxy for Coal (ARA)

The basis for the index is the cost of coal delivered to the Amsterdam, Rotterdam area, which is used to settle contracts financially.

The time variations of the index is presented in Figure 5. In the graph, a recent dramatic decrease in coal prices is noteworthy.

Figure 5. Time variations of ICE Europe Rotterdam Coal Futures Index

4.1.6. ICE UK NBP Natural Gas Futures as a Proxy for Natural Gas (NBP)

The index includes contracts for actual delivery of Natural Gas via the transfer of rights at the United Kingdom.

As demonstrated in Figure 6, naturas gas demonstrates a similar pattern with coal, after a sharp decrease, a smooth increasing trend is monitored.

Figure 6. Time variations of ICE UK NBP Natural Gas Futures Index

4.2. Descriptive Statistics

The summary of the descriptive statistics is presented in Table 2 for the green bond, carbon, renewable and non-renewable markets. First, solar energy has the highest mean with 7.83, followed by global clean with 7.255. Among the selected indices, natural gas has the lowest mean with -0.086 and it is the only indices that has a negative mean. Namely all indices have an increasing trend at the period. Highest standard deviation is observed at natural gas with 0.926, yet the least is green bond with 0.116. This may represent that the green bond has smoother trend compared to other indices and natural gas spread out over a wider range.

Table 2. Descriptive Statistics

	GREEN BOND	CARBON	GLOBAL CLEAN	SOLAR	COAL	NATURAL GAS
Mean	4.931	3.403	7.255	7.830	4.594	-0.086
Median	4.966	3.501	7.411	8.065	4.446	-0.152
Maximum	5.105	4.040	7.957	8.586	5.809	2.017
Minimum	4.664	2.484	6.505	6.772	3.947	-2.275
Std. Dev.	0.116	0.456	0.360	0.481	0.506	0.926
Skewness	-0.466	-0.064	-0.439	-0.616	0.669	0.041
Kurtosis	1.908	1.322	1.870	1.930	2.303	2.169
Jarque-Bera	102.921	141.223	102.212	133.014	113.834	34.788
Probability	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Observations	1198	1198	1198	1198	1198	1198

Note: “*” signifies the statistical significance at 1% level.

Regarding skewness, green bond, carbon, global clean and solar have a negative value, meaning that the distribution of data is negatively skewed. Yet, coal and natural have positive values and positively skewed. For kurtosis, all the values are positive for all indices. Therefore, it can be said that tails of distributions are thick and heavy – *leptokurtic* – since they are above the Mesokurtic distribution level. Lastly, Jarque-Bera (JB) test outcome rejects normality in all cases.

The time series of the selected indices is checked with the ADF unit root test. The unit root test with two specifications, intercept and intercept-trend respectively, are applied on the level and first differences of the series. The results of the ADF unit root tests which are shown in Table 3, indicate that all the data series are nonstationary at level. However, after taking the first difference of the series, they are all stationary at 1% significance level. The ADF test results show that all the variable series were integrated series of order I (1).

Table 3. Unit Root Test Results

Variable	Level				First Difference			
	ADF				ADF			
	Lag Lenght	Lag Lenght	Constant	Constant Trend	Lag Length	Lag Length	Constant	Constant Trend
Green Bond	1	1	-0.0223 (0.933)	-1.625 (0.782)	0	0	-31.012* (0.000)	-31.091* (0.000)
Carbon	0	0	-0.902 (0.787)	-1.986 (0.607)	1	1	-22.738* (0.000)	-22.728* (0.000)
Global Clean	7	7	-1.879 (0.342)	-0.749 (0.968)	6	6	-11.305 (0.000)	-11.476* (0.000)
Solar	1	0	-1.928 (0.319)	-0.286 (0.991)	0	0	-31.840* (0.000)	-31.957* (0.000)
Coal	4	4	-1.282 (0.639)	-1.956 (0.623)	3	3	-16.431* (0.000)	-16.424* (0.000)
Natural Gas	0	0	-1.282 (0.639)	-2.018 (0.590)	0	0	-34.291* (0.000)	-34.280 (0.000)

Note: "*" signifies the statistical significance at 1% level.

The correlation matrix is presented in Table 4. The results show the existence of a positive correlation between green bond – global clean, green bond – coal, carbon – global clean, carbon – solar, carbon – coal, carbon – natural gas, global clean – solar, global clean – coal, global clean – natural gas, solar – coal, solar – natural gas, coal – natural gas. However, there exists a negative correlation between green bond with carbon, solar and natural gas markets.

The highlighting outcome of the results is that green bond mainly has a negative correlation with other assets and the correlation level is lower. The strongest correlations are observed between solar and global clean, as well as natural gas and coal.

Table 4. Unconditional Correlation Matrix

	Carbon	Global Clean	Solar	Coal	Natural Gas
Green Bond	-0.541	0.007	-0.037	0.715	-0.453
Carbon		0.697	0.725	0.810	0.827
Global Clean			0.993	0.467	0.601
Solar				0.480	0.596
Coal					0.891

Lastly, Engle’s (1982) ARCH – LM test is also applied for detecting autoregressive conditional heteroscedasticity of the time series and the results are demonstrated in Table 5. The results show that applying ARCH alterations is possible for estimating the return series of selected indices.

Table 5. ARCH – LM Results

Market	**ARCH-LM Statistics**	**Prob. Chi-square**
Green Bond	9.899	0.007
Carbon	29.146	0.000
Solar	90.095	0.000
Renewable Energy	40.324	0.000
Coal	24.358	0.000
Natural Gas	18.773	0.000

Note: "*" signifies the statistical significance at 1% level.

The outcomes of the unit root test, along with the LM test statistics, align with the findings of the descriptive statistics, underlining the need for the utilization of a time-varying volatility model in the implementation of an empirical study aimed at analyzing spillover effects among variables.

CHAPTER 5: EMPIRICAL RESULTS

This chapter encompasses the mean and volatility spillover effects between green bond and other indices, namely, carbon, solar, clean energy, coal and natural gas. Tables 6 – 8 – 10 demonstrate the empirical results of VAR – BEKK – GARCH implementation, and the summary findings are available in Tables 7 – 9 – 11.

The coefficient $\delta(1)_{11}$ represents the green bond return, and the coefficient $\delta(1)_{22}$ represents the carbon, solar, clean energy, coal and natural gas indices, respectively in Tables 6-8-10. To begin with the first-moment relationship, $\delta(1)_{12}$ indicates the lagged spillover effects in mean from green bond return to other variables of carbon (presented in Table 6), solar and clean energy (presented in Table 8) and coal and natural gas (presented in Table 10). Yet, $\delta(1)_{21}$ represents the lagged spillover in the opposite direction, namely, from carbon, solar, clean energy, coal and natural gas to green bond.

The cross-market shock effects are recorded by the off-diagonal parameters a_{12} and a_{21}. Namely, while a_{12} represents the spillover effect of a previous green bond shock on the current volatility of carbon, solar, clean energy, coal, and natural gas returns, a_{21} represents the same effect but for the reverse direction. (presented in Table 6 – 8 –10, respectively)

As of other off-diagonal parameters, b_{12} assesses the effects of the previous period's green bond variance on the current variance of carbon, solar, clean energy, coal, and natural gas returns, whereas b_{21} assesses the same effect but for the reverse direction. (presented in Table 6 – 8 –10, respectively).

The coefficient of all diagonal elements of matrix A and Bevaluate the variable's own previous shocks (a_{11}, a_{22}) and previous volatility (b_{11} b_{22},), meaning that the current conditional volatility of each variable are determined by their own past shocks (a_{11}, a_{22}) and conditional past volatility (b_{11} b_{22},) The coefficients of a_{11}, a_{22} which measure the ARCH effect and b_{11} b_{22}, which measure the GARCH effect in Tables 6, 8 and 10, are found to be positive and statistically significant at 1% level, supporting the presence of own conditional ARCH and GARCH effect in green bond, renewable and nonrenewable energy markets as well as carbon markets.

In terms of the mean equation results, all of these coefficients in each table are positive and statistically significant, in other words, the lagged return of each variable, namely green bond, carbon, solar, clean energy, coal and natural gas helps to forecast its own current short-term results. The empirical results indicate the existence of bilateral return spillovers between green bond and all other renewable and nonrenewable energy markets and carbon market. Namely, current green bond returns can be projected via using previous returns of carbon, solar, clean energy, coal and natural gas and vice versa.

Regarding the shock transmission and volatility spillover effects, the shock transmission is bilateral between green bond and solar and also for coal. On the other hand, the shock transmission is unilateral between green bond and carbon, and green bond is shock transmitter. The shock transmission is also unilateral between green bond and renewable energy and natural gas, yet green bond is shock receiver for both. Lastly, a bidirectional volatility spillover effect is present between green bond and solar. Yet, the volatility spillover between green bond – coal and green bond – natural gas unilateral and green bond is volatility receiver for both markets. In terms of green bond – carbon and green bond – renewable energy no volatility spillover effect is observed.

As a summary of overall empirical results, the strongest connection is obtained between green bond and solar energy, with a bidirectional cross-market and volatility transmission. Surprisingly, the volatility of the green bond and carbon does not intercourse each other whereas during the crisis times, shocks in green bond affect the carbon returns, meaning that green bond acts as a shock transmitter. In terms of green bond – renewable energy nexus, there is again no volatility spillover, yet green bond acts as a shock receiver during crisis times. In terms and shock and volatility, a strong connection also observed between green bond and non-renewable market, and it is proofed that green bond is a volatility receiver from both coal and natural gas. The empirical results are partially coherent with the findings of Liu et al. (2020), Naeem et al. (2021), Tiwari et al. (2022) and Dwumfour et al. (2022).

Thus, it can be concluded that the study's first hypothesis—*that there are volatility spillover effects between green bonds, carbon, renewable energy, and non-renewable energy* —is supported by the empirical data. Despite the fact that green bonds and solar energy have the strongest connections among the markets that were chosen, there is no evidence of volatility spillover effects between green bonds and renewable energy sources. The components of the chosen indices could be the cause; as mentioned in Chapter 3, the renewable energy index includes a range of renewables, including biomass and wind, and vice versa.

The empirical findings also partially support the second hypothesis. It is shown that in times of crisis, green bonds can be used as a hedging tool for natural gas, renewable energy, and carbon. Furthermore, the returns on green bonds can offset the effects of price fluctuations in non-renewable energy since it acts as a volatility receiver from non-renewable energy returns. However, given how strongly green bonds and solar energy are correlated, green bonds might serve as a diversifier rather than a hedging mechanism.

Table 6. Projected findings of volatility spillover effects between Green Bond and Carbon based on the full VAR-BEKK-GARCH model.

	CARBON
Panel A. Mean Equation	
$\delta(1)_{11}$	0.996 [9435.727] *
$\delta(1)_{12}$	-0.001 [-5.171] *
μ_1	0.020 [71.404] *
$\delta(1)_{21}$	0.006 [20.336] *
$\delta(1)_{22}$	0.999 [2697.167] *
Panel B. Variance Equation	
μ_2	-0.030 [-29.688] *
c_{11}	0.000 [4.499] *
c_{21}	0.004 [0.311]
c_{22}	0.005 [5.365] *
a_{11}	0.273 [11.134] *
a_{12}	0.222 [1.844] ***
a_{21}	-0.000 [-0.054]
a_{22}	0.314 [11.406] *
b_{11}	0.958 [129.092] *
b_{12}	-0.043 [-1.049]
b_{21}	-0.006 [-0.192]
b_{22}	0.914 [48.156] *

Notes: The mean equations' constant terms are μ_1 and μ_2 . The variables' own lag effects are captured in the mean by $\delta(1)_{11}$ and $\delta(1)_{22}$, where variable *1* represents green bond *2* represents carbon. Lagged spillovers in mean from green bond return to carbon are represented by $\delta(1)_{12}$, and the corresponding effect in the opposite direction is indicated by $\delta(1)_{21}$. The variance equation contains three constant terms, respectively, c_{11}, $c_{21}$and c_{22}. The ARCH effect in the variable is represented by $a_{11}$and a_{22}. The impact of prior shock on green bond to the volatility of carbon stock returns is measured by a_{12} and the impact in opposite direction is measured by a_{21}. The GARCH terms, $b_{11}$and b_{22}indicate the GARCH terms, represent the series' volatility persistence. b_{12} calculates the impact of the green bond variance from the previous period on the variance of carbon returns in the present. The spillover effect is measured in the opposite direction by b_{21}. T-statistics are represented by numbers enclosed in square brackets. Statistical significance is indicated by the symbols, *, ** and *** at the 1%, 5% and 10% levels respectively.

Table 7. Summary of projected results for the conditional mean and conditional variance equations between green bond and carbon markets.

	Carbon
Panel A. Mean Spillovers	
Green Bond	↔
Panel B. Shock Transmission	
Green Bond	→
Panel C. Volatility Spillovers	
Green Bond	-

Notes: A bidirectional volatility transmission is indicated by ←, a unilateral volatility transmission by → or ←, and no volatility transmission is indicated by -. In the first column, ← indicates that the related commodity is a volatility receiver, and → indicates a volatility transmitter.

Table 8. Projected findings of volatility spillover effects between Green Bond and Solar and Renewable Energy based on the full VAR-BEKK-GARCH model.

	SOLAR	**RENEWABLE ENERGY**
Panel A. Mean Equation		
$\delta(1)_{11}$	0.999 [14008.690] *	1.000 [3964.098] *
$\delta(1)_{12}$	-0.000 [-13.439] *	-0.000 [-2.730] *
μ_1	0.004 [31.772] *	0.004 [7.769] *
$\delta(1)_{21}$	0.008 [74.050] *	0.007 [58.320] *
$\delta(1)_{22}$	0.997 [11035.889] *	0.997 [3546.840] *
Panel B. Variance Equation		
μ_2	-0.022 [-49.130] *	-0.018 [-12.799] *
c_{11}	0.000 [18.920] *	0.000 [5.012] *
c_{21}	-0.001 [-2.541] **	-0.000 [-1.365]
c_{22}	0.002 [5.377] *	0.001 [4.627] *
a_{11}	0.229 [30.545] *	0.246 [9.014] *
a_{12}	-0.200 [-2.093] **	-0.176 [-1.802]
a_{21}	0.017 [4.190] *	0.012 [1.836] ***
a_{22}	0.265 [14.129] *	0.012 [13.780] *
b_{11}	0.965 [345.579] *	0.960 [106.416] *
b_{12}	0.063 [2.372] **	0.048 [1.518]
b_{21}	-0.003 [-3.243] *	0.001 [-0.735]
b_{22}	0.955 [154.938] *	0.948 [130.204] *

Notes: The mean equations' constant terms are μ_1 and μ_2 ..The variables' own lag effects are captured in the mean by $\delta(1)_{11}$ and $\delta(1)_{22}$, where variable *1* represents green bond *2* represents solar and renewable energy, respectively. Lagged spillovers in mean from green bond return to solar and renewable energy are represented by $\delta(1)_{12}$, and the corresponding effect in the opposite direction is indicated by $\delta(1)_{21}$, respectively. The variance equation contains three constant terms, respectively, c_{11}, $c_{21}$and c_{22}. The ARCH effect in the variable is represented by $a_{11}$and a_{22}. The impact of prior shock on green bond to the volatility of solar and renewable energy returns is measured by a_{12} and the impact in opposite direction is measured by a_{21}, respectively. The GARCH terms, $b_{11}$and b_{22}indicate the GARCH terms, represent the series' volatility persistence. b_{12} calculates the impact of the green bond variance from the previous period on the variance of solar and renewable energy returns in the present, respectively. The spillover effect is measured in the opposite direction by b_{21}. T-statistics are represented by numbers enclosed in square brackets. Statistical significance is indicated by the symbols, *, ** and *** at the 1%, 5% and 10% levels respectively.

Table 9. Summary of projected results for the conditional mean and conditional variance equations between green bond and solar and renewable energy markets.

	Solar	**Renewable Energy**
Panel A. Mean spillovers		
Green Bond	↔	↔
Panel B. Shock Transmission		
Green Bond	↔	←
Panel C. Volatility Spillovers		
Green Bond	↔	-

Notes: A bidirectional volatility transmission is indicated by ←, a unilateral volatility transmission by → or ←, and no volatility transmission is indicated by -. In the first column, ← indicates that the related commodity is a volatility receiver, and → indicates a volatility transmitter.

Table 10. Projected findings of volatility spillover effects between Green Bond and Coal and Natural Gas based on the full VAR-BEKK-GARCH model.

	COAL	NATURAL GAS
Panel A. Mean Equation		
$\delta(1)_{11}$	0.993 [5319.24] *	0.995 [10569.275] *
$\delta(1)_{12}$	-0.001 [-11.671] *	-0.000 [-8.450] *
μ_1	0.039 [24.458] *	0.020 [45.053] *
$\delta(1)_{21}$	0.016 [37.804] *	0.049 [31.389] *
$\delta(1)_{22}$	0.998 [1067.938] *	1.000 [512.510] *
Panel B. Variance Equation		
μ_2	-0.077 [-26.482] *	-0.246 [-29.987] *
c_{11}	0.000 [10.524] *	0.000 [4.624] *
c_{21}	-0.000 [0.899]	-0.004 [-2.29429] **
c_{22}	0.002 [5.632] *	0.007 [54.772] *
a_{11}	0.244 [11.175] *	0.222 [12.155] *
a_{12}	0.222 [2.830] **	-0.329 [-1.541]
a_{21}	0.003 [0.054] ***	-0.006 [-5.207] *
a_{22}	0.353 [14.492] *	0.402 [15.285] *
b_{11}	0.964 [182.942] *	0.965 [218.914] *
b_{12}	-0.018 [-0.933]	0.070 [1.023]
b_{21}	-0.001 [-2.401] **	0.002 [7.443] *
b_{22}	0.941 [134.711] *	0.920 [116.281] *

Notes: The mean equations' constant terms are μ_1 and μ_2 . The variables' own lag effects are captured in the mean by $\delta(1)_{11}$ and $\delta(1)_{22}$, where variable *1* represents green bond *2* represents coal and natural gas, respectively.. Lagged spillovers in mean from green bond return to coal and natural gas are represented by $\delta(1)_{12}$, and the corresponding effect in the opposite direction is indicated by $\delta(1)_{21}$, respectively. The variance equation contains three constant terms, respectively, c_{11}, $c_{21}$and c_{22}. The ARCH effect in the variable is represented by $a_{11}$and a_{22}. 6. The impact of prior shock on the green bond to the volatility of coal and natural gas returns is measured by a_{12} and the impact in opposite direction is measured by a_{21}, respectively. The GARCH terms, $b_{11}$and b_{22}indicate the GARCH terms, represent the series' volatility persistence. b_{12} calculates the impact of the green bond variance from the previous period on the variance of coal and natural gas returns in the present, respectively. The spillover effect is measured in the opposite direction by b_{21}. 10. T-statistics are represented by numbers enclosed in square brackets. Statistical significance is indicated by the symbols, *, ** and *** at the 1%, 5% and 10% levels respectively.

Table 11. Summary of projected results for the conditional mean and conditional variance equations between green bond and coal and natural gas markets.

	Coal	**Natural Gas**
Panel A. Mean spillovers		
Green Bond	↔	↔
Panel B. Shock Transmission		
Green Bond	↔	←
Panel C. Volatility Spillovers		
Green Bond	←	←

Notes: A bidirectional volatility transmission is indicated by ←, a unilateral volatility transmission by → or ←, and no volatility transmission is indicated by -. In the first column, ← indicates that the related commodity is a volatility receiver, and → indicates a volatility transmitter.

CHAPTER 6: CONCLUSION & POLICY IMPLEMENTATIONS

This thesis investigates the return and volatility spillovers between green bond, carbon, renewable and non-renewable markets using daily data spanning from over the period November 7th, 2018 to November 30th, 2023. To achieve this, we use the Solactive Green Bond Index as a measure for green bond returns, IHS Markit Global Carbon Index which consists of European Union Allowances (EUA), California Carbon Allowances (CCA) and the Regional Greenhouse Gas Initiative (RGGI) as a measure for carbon market. On the other hand, for the renewable energy market examination, EQM Solar Energy Index is utilized for solar, and S&P Global Clean Index is also used for its feature of including major renewable energy assets such as wind, hydro and biomass. Lastly, for the non-renewable energy market, ICE Europe Rotterdam Coal Future Index is used as a proxy for coal, and ICE UK NBP Natural Gas Future Index is as a proxy for natural gas. The dataset is composed of 1198 observations.

To investigate the return and volatility spillover effects, VAR – BEKK – GARCH model is employed due to its highlighting feature that is imposing no limitation on the correlation structure among the variables. While employing the model, green bond is set as the main variable and other variables are adjusted respectively. Our empirical findings demonstrated that there are return spillover effects between green bond and carbon, renewable and non-renewable energy markets, yet the volatility and shock spillovers alter depending on the market.

When starting the study, we aim to answer two research questions; "*Are there any return and volatility spillover effects between green bond, renewable and non-renewable energy and carbon markets?"* and *"Do green bond act as hedging tool for price fluctuations in renewable energy, non-renewable energy and carbon markets?"*. And then, we test the two main hypotheses mentioned above. In line with the research questions, hypotheses of the study are developed as *"There exist volatility spillover effects among green bond, renewable, non-renewable energy stocks, and carbon markets."* and *"Green bond does act as a hedging tool for price fluctuations renewable, non-renewable and carbon markets."*.

Both hypotheses of the study are acknowledged with giving anecdotes in Chapter 5. As first, our findings show that there are strong return spillover effects between green bond and carbon, renewable and non-renewable energy market and we demonstrated that current period returns in the green bond market can be predicted using past returns in carbon, solar, clean energy, coal, and natural gas, and vice versa. In terms of volatility spillover and shock transmission, it is shown that there is no volatility spillover between green bond and carbon market and renewable energy market, whereas green bond can act as a shock transmitter for carbon, and as a shock receiver for renewable energy during crisis times. On the other hand, it is observed that green bond is a volatility receiver from non-renewable energy resources.

Regarding our question about the hedging effect of green bond against carbon, renewable and non-renewable energy markets, there are several findings. First of all, the results reveal that there exists no volatility spillover between green bond and carbon markets, whereas green bond is shock transmitter during crisis times. Meaning that green bond may have hedging effect against carbon market, also it can be used for portfolio diversification for both investors and ETS companies.

On the other hand, although again no volatility spillover effect is found between green bond and renewable energy, in terms of solar energy, there is a strong two-way connection for returns, volatility and shock spillovers, whereas green bond is a shock receiver from renewable energy. Therefore, said the findings specify that there is a strong symmetrical correlation between green bond and solar energy. Lastly, besides the bilateral correlation, it is noteworthy that green bond is a shock receiver from both coal and natural gas, namely, shocks in coal and natural gas affect the green bond, yet green bond does not have such an impact on these assets. In the light of these findings, it can be said that green bond may have hedging effect against coal and natural market during crisis times, yet it can be utilized for portfolio diversification for both renewable and non-renewable energy.

These findings may also point out certain policy implementations for governments. Firstly, since there is a strong connectedness between solar energy and green bond, when green bond prices and solar energy prices move in tandem, as a result, green bonds may experience a price externality (Tiwari et al., 2022). Another interpretation is that the lack of incentives regarding green bonds may negatively affect solar energy prices, which is a crucial pillar of energy transmission process. Lastly, since green bond is a shock receiver from non-renewable energy market, green bond may provide a smoother energy transition if prompted by government policies. In given conditions, governments can provide certain financial incentives such as interest discounts and credit rating mechanisms for green bonds, and transparency, institutional mechanisms, clarifying and standardizing the issuance procedures are crucial as the financial incentives. The governments may also emphasize on providing supervision mechanisms by establishing regulatory authorities for monitoring and certification of green projects, organizing etudes to increase public awareness. Since the investors substantially value the issuer, government-initiated green bonds would also have positive effect for creating an increasing trend.

For corporations, since the investors’ reaction is same for green bond as for the identical traditional bond, issuance of green bonds may increase the reputation of the company among environmentally aware investors without any causalities and enhance the public relations. In contemporary business theory, it is commonly accepted that socially responsible corporations have higher valuation and lower risk.

For the perspective of portfolio managers, firstly our study claims that green bond prices can be predicted by using carbon, renewable and non-renewable energy returns. Second, as the green bond has a bilateral shock transmission relationship with carbon, renewable energy and natural gas, green bond can be added for a balanced portfolio during turbulent times. For instance, green bond would have weakened the effects of the natural gas crisis between Europe and Russia during the invasion of Ukraine. Furthermore, since non-renewable energy traditionally tends to demonstrate sharper fluctuations, green bond can provide a safe haven for the investors.

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