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# Green Bond Returns and the Dynamics of Green and Traditional Financial Markets: A Thick Pen Analysis

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## Abstract

This paper analyses the relationship between green bond markets and both green and traditional financial markets using the Thick Pen Measure of Association, a visually interpretable tool for analyzing comovement across different time scales. It finds, first, that the relationships between these markets shift over time, with a strong influence of events like COVID-19 and the Ukraine war. Second, green bond returns closely track benchmark bonds but show weaker, sometimes declining, links to stocks, which underscores their diversification potential. Short-term green bond moves, however, remain tied to the stock market's long-term environment, especially in times of stress.

**Keywords:** Green bonds, financial markets, comovement, association thickness measure, data science

**JEL-classification:** C14, C32, C46, G12, Q56

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# 1 Introduction

The global transition towards clean energy, alongside growing concerns about climate change and sustainability, has propelled green investments into the spotlight, capturing the attention of policymakers, investors, and researchers alike. Since the issuance of the first green bond by the European Investment Bank (EIB) in 2007, the green bond market has experienced significant growth, often referred to as a “green bond boom” ([Morgan Stanley, 2017](#)). This strong demand is driven by investors’ increasing interest in sustainable investments, which are vital for financing the transition to a carbon-neutral society. Yet, the appeal of green bonds extends beyond environmental considerations: following the Global Financial Crisis, investors began reassessing their portfolios in light of the reduced diversification benefits offered by equity markets. Consequently, understanding the relationship between green bonds and other financial markets, both green and conventional, has become increasingly important, as insights into their co-movement can aid portfolio optimization and shed light on the role of green bonds as a key instrument for supporting the energy transition.

To investigate return co-movement, in particular changes in the co-movement dynamics, between the green bond and other, green as well as conventional, financial markets, we use an approach called the ‘Thick Pen Measure of Association (TPMA)’ of [Fryzlewicz and Oh \(2011\)](#), which was later extended by [Jach \(2021\)](#) to ‘Multi-thickness Thick Pen Measure of Association

(MTTPMA)'. The key advantages of these two measures of association can be summarized as follows. First, they are applicable to both stationary and non-stationary time series. Second, they can be used in bivariate as well as multivariate settings. Third, being time-varying, they capture changes in the degree of co-movement over time. Fourth, they can detect co-movement in both long-run and short-run components of the data. Fifth, they are visually interpretable, and finally, they quantify co-dependence across different time scales. In short, the method accommodates diverse types of data while capturing complex dependence structures. TPMA technique allows us to empirically examine co-dependencies between the green bond and other markets for a given time scale or for a range of time scales, whereas the MTTPMA technique allows for the examination of codependencies across different time scales; that is, capturing a short-term component of a green bond series with long-term components of a green equity series, or the other way around. This method has been popularized in empirical finance and energy economics. [Gronwald and Jin \(2024\)](#) investigate the integration of world crude oil markets; [Wadud, Gronwald, Durand, and Lee \(2023\)](#) the co-movement of commodity and equity markets.

This method has several advantages over standard established approaches. Conventional dynamic correlation models, such as DCC-GARCH, rely on stationarity assumptions or pre-filtering, focus on linear co-movement, and provide a single aggregate dependence measure. As a result, they cannot separate short- and long-run dynamics, ignore frequency-specific interac-

tions, and offer limited scale-specific or visual interpretability. Quantile connectedness models focus on extreme co-movements, offering insights into shock propagation during extreme events. However, they overlook overall co-movement, central distribution interactions, and frequency-specific dynamics, and their visualizations provide limited intuition beyond extreme-event scenarios. In summary, conventional dynamic correlation and quantile connectedness methods are limited in capturing frequency-specific, full-range, or visually interpretable co-movements. Frequency-domain techniques, such as cross-correlograms and the long-run covariability measures of [Müller and Watson \(2018\)](#), decompose series into short- and long-term components, providing a clearer, time-scale-specific view of dependencies that aggregate correlation measures can obscure. The methods used in this paper share some similarities with that type of approach.

Green bond prices co-move with other financial assets due to shared exposure to macroeconomic conditions, market-wide risk sentiment, and policy or transition risks. Portfolio rebalancing, liquidity effects, and cross-market spillovers further strengthen these linkages, causing co-movement to vary over time. The theoretical motivation for examining green bond–equity connectedness builds on [Dean, Faff, and Loudon \(2010\)](#), who document asymmetric return and volatility spillovers between bond and equity markets. From a broader perspective, our analysis also contributes to the literature assessing green bonds as climate finance instruments ([Flammer, 2021](#); [Gronwald & Wadud, 2025](#)).

Our findings can be summarized as follows: First, the degree of comovement between green bond returns and those of other financial markets, both green and conventional, evolves over time. While major events such as the outbreak of COVID and the Ukraine war are significant drivers of these changes, we also observe shifts in co-movement as early as 2017. Second, the strongest co-movement is found between green bond returns and the returns of other benchmark bond markets. This suggests that the fundamental factors driving general bond markets also influence green bond markets. Third, the co-movement with stock market returns is weaker and, in some cases, shows a declining trend over time. At the same time, short-term movements in the green bond market are strongly related to the long-term stock market environment, especially during turbulent periods such as the COVID-19 outbreak and the Ukraine war.

The remainder of the paper is organised as follows: the following [Section 2](#) provides a detailed overview of the literature and discusses how this paper contributes. [Section 3](#) describes both the data and the method used in this paper. [Section 4](#) presents the empirical results and [Section 5](#) offers some concluding remarks.

## **2 Literature Review and Contribution**

This analysis contributes to a rapidly growing body of academic literature. The closest study this research is related to is [Aroui, Mhadhbi, and Shahrour's](#)

(2025) analysis of the dynamic connectedness and hedging effectiveness between green bonds, ESG indices, and traditional assets. The paper finds that green bonds and ESG indices are strongly but time-varyingly connected to traditional assets, with green bonds offering effective yet conditional hedging and diversification benefits, especially during market stress.

Among other recent contributions, [Karim, Lucey, Naeem, and Yarovaya \(2024\)](#) investigate the extreme risk dependence between green bonds and broader financial markets. They highlight the significant diversification benefits that green bonds can offer, along with safe-haven and hedging opportunities. [Arif, Hasan, Alawi, and Naeem \(2021\)](#) find that green and conventional markets are usually weakly connected — offering diversification benefits—but their connectedness jumps sharply during crises like COVID-19, reducing those benefits; [Naeem, Conlon, and Cotter \(2022\)](#) show that green bonds generally provide diversification benefits, but under extreme market stress their risk spillovers with other assets rise sharply. Our results are overall consistent with this. Additionally, [Ren, Xiao, Duan, and Urquhart \(2024\)](#) explore the dynamic correlations and inefficiencies between fossil energy markets and green markets, while [Adekoya, Oliyide, Asl, and Jalalifar \(2021\)](#) focus on the differences in market efficiency and volatility persistence between green and conventional bonds. For one of the earliest academic contributions, see [Flammer \(2020\)](#).

There is a substantial and closely related literature on climate risk and green investments. [Bouri, Rognone, Sokhanvar, and Wang \(2023\)](#) show that

climate-related risks—particularly transition risk—significantly predict green bond volatility more than returns, underscoring their sensitivity to climate policy and the low-carbon transition. Similarly, [Arfaoui, Naeem, Maherzi, and Kayani \(2024\)](#) find that green investment funds can hedge extreme climate-risk events, providing diversification and safe-haven benefits rather than exhibiting heightened tail risk during periods of climate stress. [Rab-bani, Kiran, Cepni, and Naeem \(2025\)](#) further show that green investment, especially when coupled with strong ESG performance, reduces firms’ exposure to climate risk and enhances resilience to environmental and regulatory shocks.

Our analysis complements this literature by showing that co-movement between green bond markets and environmental stock markets is stronger than with broad equity markets or oil- and gas-intensive sectors. This suggests that green bonds offer partial insulation from climate and transition risks that primarily affect fossil energy stocks through regulation, carbon pricing, and stranded-asset concerns. At the same time, environmental stocks are not risk-free, as they remain exposed to policy uncertainty, subsidy changes, technological competition, and macro-financial conditions, leading to spillovers and time-varying co-movement across green and brown assets. Finally, we also document strong co-movement between green bonds and conventional bond markets, implying that exposure to traditional fixed-income risks remains an important vulnerability of green bonds.

Other notable studies examine the interconnectedness of crude oil and

green bond markets (Yousaf, Mensi, Vo, & Kang, 2024) and volatility spillovers between green bonds and new energy markets (Wu & Qin, 2024). Worth mentioning are also studies on the relationship between green bonds and various financial markets such as Chatziantoniou, Abakah, Gabauer, and Tiwari (2022); Hung (2021); Reboredo and Ugolini (2018, 2020). Finally, the relationship between green bond and commodity markets (Naeem, Adekoya, & Oliyide, 2021), and the carbon market (Jin, Han, Wu, & Zeng, 2020; Ren, Zhang, Yan, & Gozgor, 2022) is also the subject of numerous other studies.

## 3 Data and Method

### 3.1 Data

The data used in this paper is similar to that in related studies such as Pham (2021) and Gronwald and Wadud (2025), but a more comprehensive set of financial indices is used to allow for a more thorough analysis of the dynamics of the green bond market within the broader financial domain. In specific, this study uses the S&P Dow Jones Green Bond Index to represent the green bond market. To capture the interaction between green bond and equity markets, this study considers the NASDAQ OMX Green Economy Stock Index. This index encompasses a diverse set of firms operating in sectors such as clean energy, green buildings, green transportation, global water management, solar energy, and wind energy. In addition, this study investigates the co-movement between green bonds and broader financial markets,

incorporating indices such as the MSCI World Index, MSCI World Energy Index, and MSCI Global Environment Index. The MSCI World Index serves as a proxy for global equity performance, while the MSCI World Energy Index reflects the dynamics of the conventional energy sector, allowing for a comparative analysis between fossil-fuel-dominated investments and green financial instruments. Meanwhile, the MSCI Global Environment Index is included to specifically assess the relationship between green bonds and environmentally focused equity investments. The Bloomberg Treasury Index, Bloomberg Corporate Bond Index, and Bloomberg Aggregate Bond Index are also integrated into the analysis to capture the interaction between green bonds and traditional bond markets.

To take into account the potential influence of policy uncertainty, this study also considers the US economic policy uncertainty (EPU) index. This index contextualises the broader economic environment within which these relationships are examined. Given that green bonds are often linked to government policy incentives and regulatory shifts, the inclusion of the EPU Index facilitates a deeper exploration of policy-driven market volatility effects on green financial instruments. A concise description of all indices employed in this research is presented in Table 1.

To explore the co-movement of the green bond markets with green and conventional markets, we use daily log-return on prices of the above-mentioned series with the sample period spanning from 14 October 2014 to 15 Feb 2024, a total of 2399 observations.

Table 1: Description of data

Variable	Index	Benchmark	Bloomberg Ticker
GB	S&P Dow Jones Green Bond TR Index	Green bond	SPUSGRN
Cleanenergy	NASDAQ OMX Clean Energy-focused Index	Green equity: Clean energy	GRNCLNFO
Wind	NASDAQ OMX Wind	Green equity: Wind energy	GRNWIND
Building	NASDAQ OMX Green Building	Green equity: Building	GRNGB
Solar	NASDAQ OMX Solar	Green equity: Solar	GRNSOLAR
Transportation	NASDAQ OMX Green Transportation	Green equity: Transportation	GRNTRN
Water	NASDAQ OMX Global Water	Green equity: Water	GWATERL
MSCI	MSCI World	General stock	MXWO
MSCIenergy	MSCI World Energy Index	Energy stock	MXWOEN
MSCIenv	MSCI Global Environment Index	Environment stock	GEIB
SPcleanenergy	S&P Global Clean Energy Index	Clean energy stock	SPGTCED
Bcorporate	Bloomberg Global Aggregate Corporate	Global bond	LGCPTRUU
Btreasury	Bloomberg Global Aggregate Treasuries	Global bond	LGTRTRUU
Baggregate	Bloomberg Global Aggregate Index	Global bond	LEGATRUU
EPU	US Economic Policy Uncertainty index	Policy uncertainty	EPU

*Source: Bloomberg terminal*

Figure 1, upper left panel, illustrates the time-varying pattern of green bond index returns. Between 2015 and 2017, volatility was relatively high, followed by a quieter period from 2018 onwards. A sharp spike in volatility occurred in 2020 due to the outbreak of the COVID-19 pandemic, causing extreme short-term returns before stabilizing back to 2015–2017 levels. Another notable increase in volatility emerged in 2022 with the outbreak of the Ukraine war. In short, there are very pronounced changes in volatility of the green bond index returns over time.

Comparing this to other markets, aggregate bond returns (upper right panel) display a very similar pattern, suggesting that green bond prices are driven by the same underlying macroeconomic and financial factors that influence the broader bond market. The MSCI index (bottom left panel) follows an intriguing trajectory: it experienced heightened volatility in 2015 and 2016, but then stabilized, followed by another increase in volatility in 2018

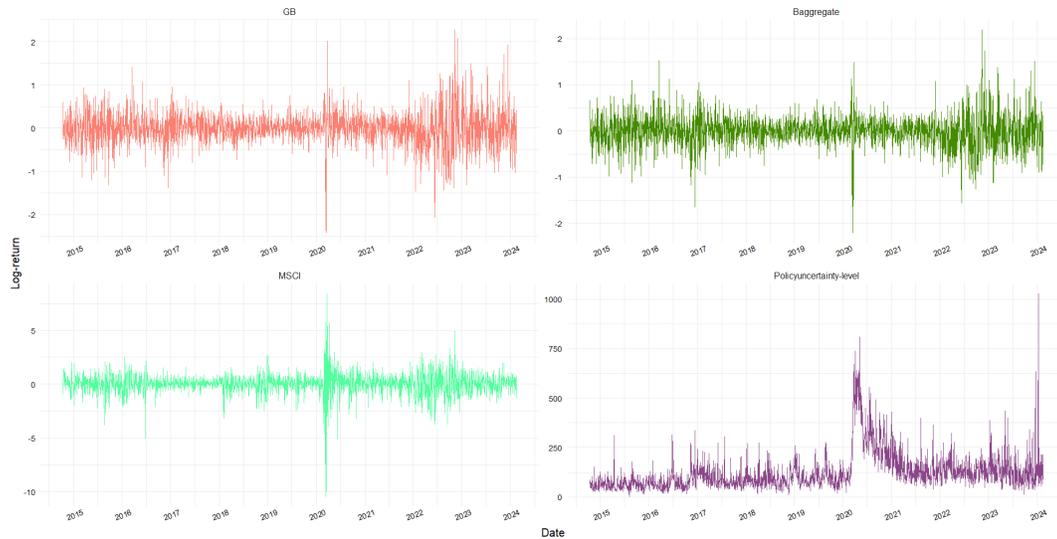


Figure 1: Daily log returns of Green Bond prices, Aggregate Bond prices, MSCI index, and level of US economic policy uncertainty index

and 2019. The COVID shock had a more prolonged effect on the MSCI index, resulting in a higher volatility in 2021, and while volatility in 2022/2023 was higher than in 2021, the relative impact was not as pronounced as in bond markets. Changes in volatility, however, occur at the same points in time.

A key factor behind these trends is uncertainty. The policy uncertainty measure, displayed in the bottom right panel of Figure 1 remained low until early 2017 but then increased and became more volatile. This appears to have impacted the MSCI index more significantly than bond markets, particularly from mid-2018 onward. The COVID-19 shock led to a more sustained rise in uncertainty, though the response in both stock and bond markets was less pronounced. From 2022 to 2024, policy uncertainty remained elevated

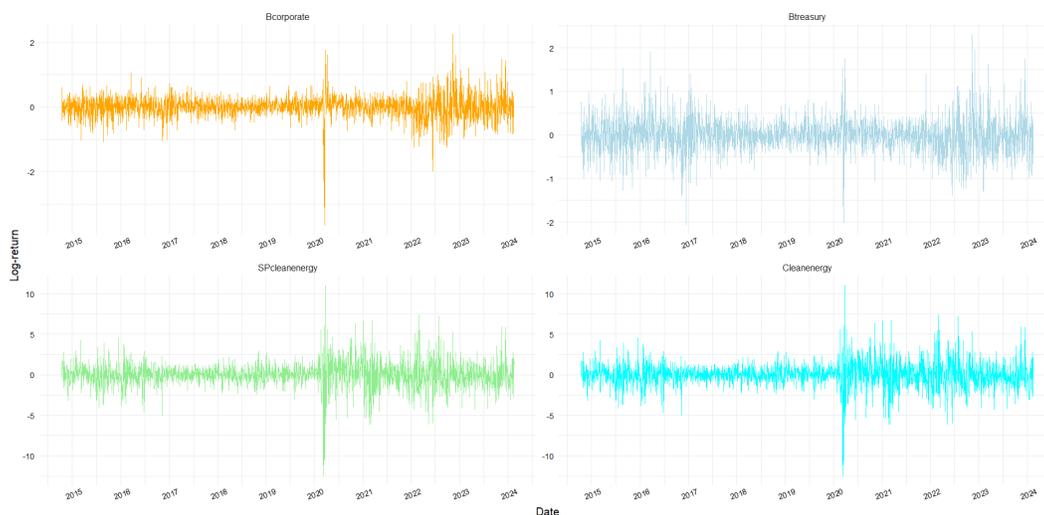


Figure 2: Daily log returns of Corporate as well as Treasury Bond prices, S&P clean energy index and NASDAQ OMX clean energy focused index

but relatively stable. As noted, both stock and bond markets reacted to the inflation shock following the outbreak of the Ukraine war.

Figure 2 presents the returns of two additional benchmark bond markets - Bloomberg Corporate Bonds and Treasury Bonds - along with returns from two broader clean energy stock markets. Worth noting is that the return patterns in Corporate Bonds closely resemble those of green bonds, though with slightly lower overall volatility. This is particularly evident in the period before 2017 and again from 2022 onward. In contrast, treasury bonds exhibit slightly higher volatility throughout the observed period. There are also smaller relative changes in the extent of volatility.

The returns of broader clean energy stock market indices reveal an interesting pattern. In particular, the volatility of the S&P Clean Energy Index

remains elevated throughout 2020 following the COVID shock, unlike the MSCI Index, where volatility declines more quickly. A similar trend is observed in the Clean Energy Stock Index, which also maintains heightened volatility during this period. Thus, the timing of changes in volatility is different from those in the broad MSCI index.

Figure 3 displays the returns of the remaining niche, specialized stock indices examined in this study, each exhibiting distinct idiosyncratic features. In particular, while some indices saw a decline in volatility after the COVID shock in 2020, others - such as Transport and Solar - did not follow this pattern. Among them, the Transport index stands out as the most volatile overall.

## 3.2 Method

The empirical framework used in this paper is based on Thick Pen Transform (TPT) introduced by [Fryzlewicz and Oh \(2011\)](#) and complementary measures derived from it by [Jach \(2021\)](#), the Thick Pen Measures of Association (TPMA) and its multiscale extension, the Multi-Thick Pen Measure of Association (MTTPMA). These methods offer a flexible, non-parametric framework to assess comovements across time and scale without imposing rigid assumptions about data stationarity. We summarise the methodological framework employed in this study; a detailed exposition is provided in [Jach \(2021\)](#), [Wadud et al. \(2023\)](#), and [Gronwald and Jin \(2024\)](#).

The methodology involves representing an univariate time series, such

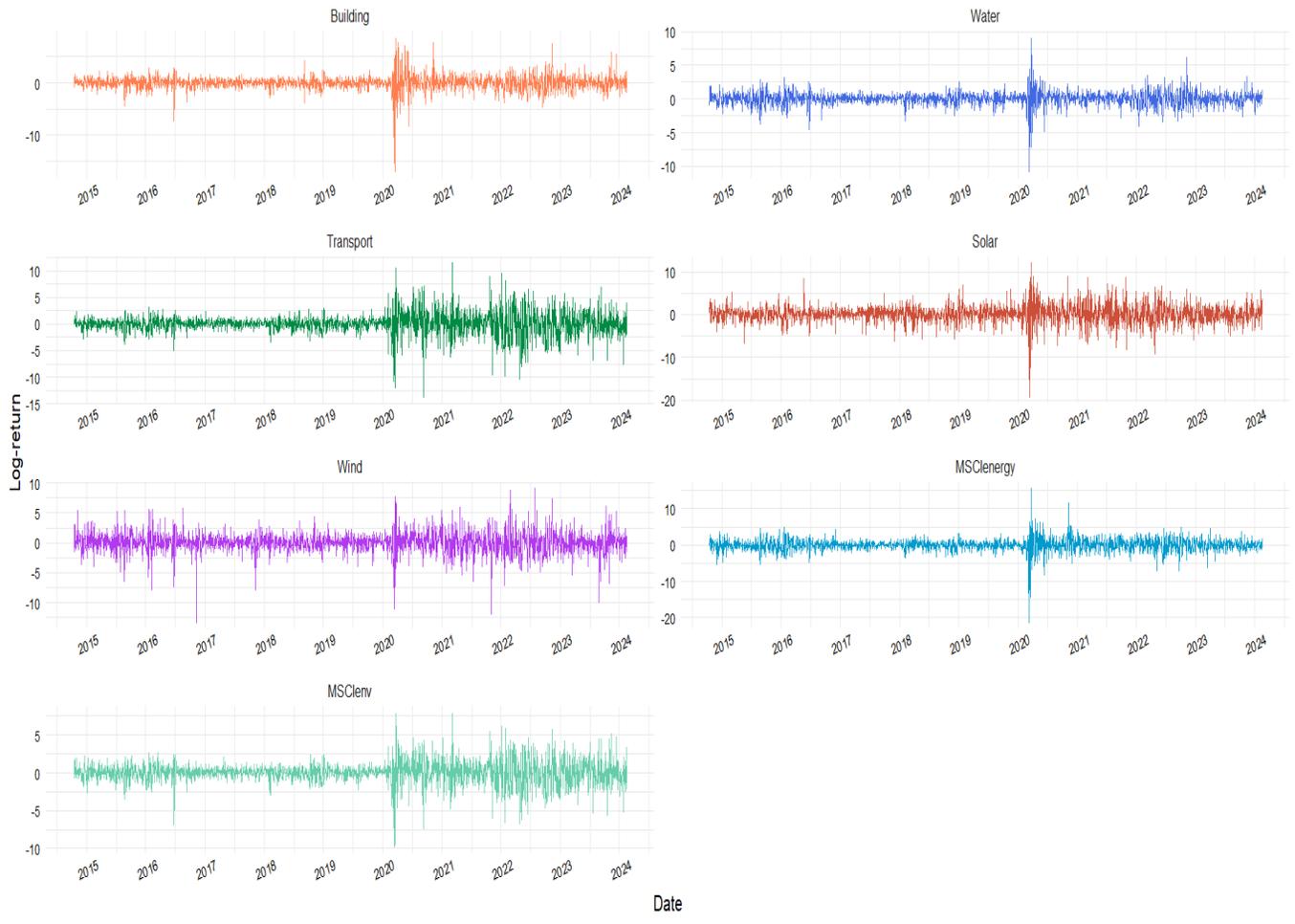


Figure 3: Remaining data

as daily log-returns, by sequentially connecting data points over time using pens of different thickness. Varying the thickness enable us to emphasise features at different frequencies: thinner thicknesses show high-frequency (short-term) dynamics, while larger thicknesses highlight lower-frequency (long-term) trends.

For a given univariate series  $X_t$  with length  $T$  and a set of positive thickness parameters  $\{\tau_1, \tau_2, \dots, \tau_n\}$ , the thick pen transformation (TPT) generates two sequences (the lower and upper boundaries) for each thickness using a look-back approach.<sup>1</sup>

$$L_t^\tau(X) = \min(X_t, X_{t-1}, \dots, X_{t-\tau})$$

$$U_t^\tau(X) = \max(X_t, X_{t-1}, \dots, X_{t-\tau})$$

These boundaries capture the features of  $X$  with respect to a varying time scale of  $\tau$ .

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<sup>1</sup>Prior to TPT computation, all time series are normalized to have zero mean and unit variance to ensure comparability.

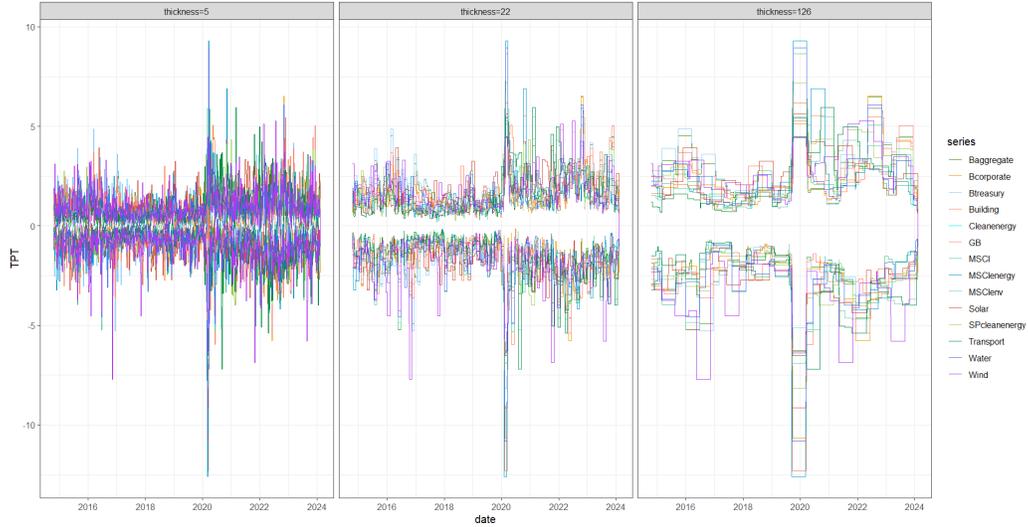


Figure 4: Thick Pen Transform of daily returns (normalised) of Green Bond Index, NASDAQ OMX Green Economy Stock indices, various indices from financial domain and global bond markets for various thicknesses up to 126 trading days (half a year).

Figure 4 displays the TPT applied to daily log-return for multiple thicknesses of up to half a year. Specifically,  $\tau = 5$  corresponds to weekly data,  $\tau = 22$  represents monthly data, and  $\tau = 126$  corresponds to half-yearly data.

After obtaining TPT representation, the TPMA quantifies the degree of overlap between multiple series at a common scale  $\tau$ . For  $K$  series, the TPMA at time  $t$  is defined as:

$$\rho_t^\tau(X^{(1)}, X^{(2)}, \dots, X^{(K)}) = \frac{\min_k(U_t^\tau(X^{(K)})) - \max_k(L_t^\tau(X^{(K)}))}{\max_k(U_t^\tau(X^{(K)})) - \min_k(L_t^\tau(X^{(K)}))} \quad (1)$$

The resulting TPMA metric ranges within  $(-1, 1]$  and evolved over time, thereby shows dynamic co-movements. A value close to 1 indicates strong co-movement, while values closer to 0 or negative suggest weak or gaps between the time series' movement.

Recognizing the need to account for cross-scale dependencies, [Jach \(2021\)](#) extended TPMA into the Multi-Thickness Thick Pen Measure of Association (MTPMA). This generalization permits each series to be transformed with an individual thickness, yielding:

$$\rho_t^{(\tau^{(1)}, \tau^{(2)}, \dots, \tau^{(K)})}(X^{(1)}, X^{(2)}, \dots, X^{(K)}) = \frac{\min_k(U_t^{\tau^{(k)}}(X^{(K)})) - \max_k(L_t^{\tau^{(k)}}(X^{(K)}))}{\max_k(U_t^{\tau^{(k)}}(X^{(K)})) - \min_k(L_t^{\tau^{(k)}}(X^{(K)}))} \quad (2)$$

Thus, MTPMA replaces the common scale assumption of TPMA with a flexible vector of scales  $\tau^{(1,2,\dots,k)}$ , allowing for cross-frequency interactions between series.

Section [3.1](#) highlights substantial variation in the volatility of the data over time. In some cases, changes in volatility are closely aligned across return series, while in others they differ markedly, both in timing and magnitude.

The Thick Pen Measure of Association would interpret unequal increases in volatility as a decline in co-movement, because the method focuses on how closely the smoothed shapes of two return series align at different time scales. When both series become more volatile but one does so much more than the other, the thick-pen boundaries diverge: the larger swings in one series cannot be matched by similarly sized movements in the other, so their curves

overlap less often. This reduced overlap is recorded as weaker association. If volatility increases similarly in both series, their boundaries expand in parallel and overlap is largely preserved; TPMA therefore shows little change in co-movement. If volatility increases synchronously, overlap can even increase. Thus, TPMA captures co-movement not by volatility levels themselves but by how similarly the two series' shapes evolve when their variability changes.

TPMA and MTPMA capture how the co-movement of returns between green bonds and other financial assets evolves across different time horizons. At short time scales, it reflects high-frequency co-movements in returns, corresponding to day-to-day or week-to-week price changes driven by market news, investor sentiment, or short-term trading strategies. At longer time scales, it reflects persistent co-movements in returns, which indicate alignment with broader market trends, macroeconomic cycles, or structural connections between markets. In other words, TPMA shows not just whether two assets' prices change together, but how strongly their returns move together over short-term versus long-term periods. This distinction helps investors separate transient correlations that may appear during volatile periods from deeper, more stable relationships that persist over months or years, and can also reveal periods when assets that usually move independently begin to co-move more closely, signaling changes in diversification benefits or systemic risk.

## 4 Results

We conduct the analysis using three thickness parameters:  $\tau = 22$ ,  $\tau = 126$ , and  $\tau = 504$ . As we use daily data, this corresponds to the 1-month-feature, 6 month-feature, and the 2-year-feature of the data.

The presentation of the results begins with the co-movement between green bond returns and Bloomberg Aggregate Bond returns, see Figure 5. The top-left panel of the figure shows that the overlap between the 1-month features of the data fluctuates around 0.75, which implies a strong co-movement. There is some time variation; the overlap dips slightly below 0.75 in 2017. However, in the latter part of the sample, particularly after 2020, the overlap stabilizes at a higher level, mostly above 0.75. A similar pattern is observed in the 6-month features of the data, where the overlap remains relatively stable over time, which reflects the smoothing out of short-term fluctuations. The overlap dips slightly in 2021 but rises significantly in 2022, approaching 1. For the 2-year features, the overlap exhibits minimal variation over time, although the increase in 2022 is clearly visible. In other words, the extent of co-movement of the short-term features of the data fluctuates continuously over time while the co-movement of the medium- and long-run features does not fundamentally change - except for the pronounced increase in 2022. This last finding indicates that, following the outbreak of the Ukraine war in 2022, the volatility patterns of the two return series became markedly more similar, with this convergence being particularly pronounced at medium- and



Figure 5: Co-movement of Green Bond and Aggregate Bond returns

long-term horizons.

Greater similarity in volatility patterns, particularly at medium- and long-term horizons, implies reduced diversification benefits as assets are more likely to experience elevated risk simultaneously, while also signalling higher systemic risk due to stronger and more persistent linkages that increase the likelihood of shock transmission and prolonged market stress. The observed higher co-movement in returns implies more uniform price signals, with prices reflecting common risk factors rather than asset-specific information. Overall, these findings suggest that green bond returns and aggregate bond market returns generally move closely together: the fundamental factors that influence the broader bond market also drive green bond prices. Although green bonds are a distinct asset class, they remain a subclass of the broader bond market - an important insight for evaluating their role as a climate finance instrument.

Moving from the TPMA on the main diagonal to the MTPMA on the sub-diagonal reveals an intriguing pattern in the overlap across time scales. The overlap between the 1-month feature of green bond and the 2-year feature of aggregate bond returns varies significantly over time (top right panel). Initially, the overlap fluctuates between 0.25 and 0.5. After a brief period of increased overlap, it drops sharply to below 0.25 in early 2018. After a short increase in overlap in early 2020 due to the COVID outbreak, the overlap remains low until the end of 2021. In 2022, however, the overlap rises once more, exceeding 0.5. This suggests a co-movement between the long-term

features of aggregate bonds and the short-term features of green bonds. In other words, short-term fluctuations in the green bond market are closely tied to conditions in the broader aggregate bond market, especially during periods of heightened stress such as early 2020 and 2022/2023. This suggests that, in turbulent times, green bond prices are driven more by general bond market dynamics and shifts in risk sentiment than by green-specific factors.

A similar pattern is observed in the overlap between the 2-year features of the green bond returns and the 1-month features of aggregate bond returns (bottom left panel), although the overlap was higher before 2018. Traditional measures of co-movement would likely fail to capture this dynamic, underscoring the value of this approach.

Having examined the co-movement between green bond returns and aggregate bond returns, we now turn to their relationship with a broad stock market index, the MSCI (see Figure 6). A striking pattern emerges: the overlap of the 1-month features between these two series is notably lower than in the previous case, fluctuating between 0.5 and 0.75, with occasional deviations above and below this range. Particularly noteworthy is the low overlap in 2018, as well as in 2023 and 2024. This latter finding is particularly intriguing, as it indicates that the co-movement of returns between these two markets weakens during the 2023 crisis period, in contrast to the stronger co-movement observed between green bond and aggregate bond returns. This divergence reflects the fact that MSCI return volatility declines more sharply in 2023 than green bond return volatility relative to 2022. A plausible ex-

S&P Green Bond and MSCI

23



Figure 6: Co-movement of Green Bonds and MSCI Stock Index returns.

planation is that green bond markets are more sensitive to inflation-related shocks and anticipated central bank responses than the broader equity market. In this sense, the result can be viewed positively, as it suggests that the factors driving MSCI equity returns do not influence green bond returns to the same extent, preserving some degree of market segmentation.

This divergence becomes even more pronounced when analyzing the 6-month and 2-year features. In 2023 and 2024, the overlap drops to 0.5, the lowest level observed in the entire sample period, following a clear downward trend. This suggests that green bond markets are increasingly behaving independently, which is beneficial from a diversification perspective because their price drivers are distinct from those of general equity markets, and it also implies a potential reduction in systemic risk, as shocks affecting equities are less likely to propagate directly to green bond markets. The cross-scale overlap also reveals interesting patterns in this case. Although the overlap between the 2-year features of green bond returns and the 1-month features of MSCI stock returns (bottom-left panel) fluctuates in a largely unsystematic manner, the top-right panel presents a pattern similar to the previously discussed relationship: particularly low in 2018 and 2019, but higher in the challenging market environments discussed above. This suggests that short-term movements in green bond returns are influenced not only by long-term trends in the broader bond market but also by developments in the stock market, reflecting their sensitivity to both fixed-income fundamentals and broader macroeconomic and market risk dynamics.



Figure 7: Co-movement of Green Bond and S&P Global Clean Energy Stock Index returns (upper panel) and MSCI Environment Stock Index returns (lower panel).

Figure 7 (upper panel) examines the co-movement between green bond returns and the returns of the S&P Clean Energy Stock Index. The overlap of the 1-month features generally ranges between 0.5 and 0.75, with occasional deviations beyond this interval, reaching its lowest levels in 2017 and 2021. Notably, the co-movement remains relatively stable in 2023, unlike the weakening observed between green bond returns and broad MSCI returns, suggesting that price signals in the green bond market continue to reflect movements in the clean energy equity sector, rather than general equity market trends.

A similar pattern is observed in the 6-month features, with a slight downward trend over time. The decline in overlap becomes more pronounced when analysing the 2-year features. Initially high at around 0.75, the overlap gradually falls below this threshold. However, this downward trend is less pronounced than in the MSCI case. Notably, even for this clean energy specific stock index, the co-movement with green bonds remains weaker than that observed between green bonds and aggregate bond markets, suggesting that green bonds are less tightly linked to equity fluctuations and continue to provide some degree of diversification, while their price signals predominantly reflect fixed-income and sector-specific dynamics rather than broad market shocks.

Figure 7 (lower panel) shows that the co-movement between green bond returns and the MSCI Environment Stock Index returns follows a broadly similar pattern compared to previous cases. However, one key difference

is the relative stability of the overlap over time, which is characterised by only minor fluctuations. The overlap is slightly lower in 2017 and noticeably higher from 2022 to 2024. This pattern is also evident in the 6-month and 2-year features, where no clear downward trend emerges. The 2-year overlap remains relatively stable at around 0.70 throughout the sample period. Interestingly, cross-scale overlap shows a sharp decline between 2018 and 2020, mirroring observations in other cases. This finding adds another layer to our understanding of how green bonds interact with different segments of the market.

For both relationships, the cross-scale analysis reaffirms that short-term movements in the green bond market are closely linked to the long-term stock market environment. Notably, this connection is evident not only during challenging market conditions but also in the period before 2018, where the overlap is higher compared to the relationship between the green bond market and the broader MSCI stock index.

Next, we examine the co-movement between green bond returns and other bond market subsets, starting with corporate bonds and then treasury bonds (see Figure 8). The overlap of the 1-month features between corporate bond returns and green bond returns is consistently high, remaining above 0.75 for most of the period, and exceeds the overlap observed between green bonds and aggregate bonds while exhibiting less temporal variation. A similar pattern is observed for the 6-month and 2-year features, where co-movement with corporate bonds remains stronger than with aggregate bonds, and notably,

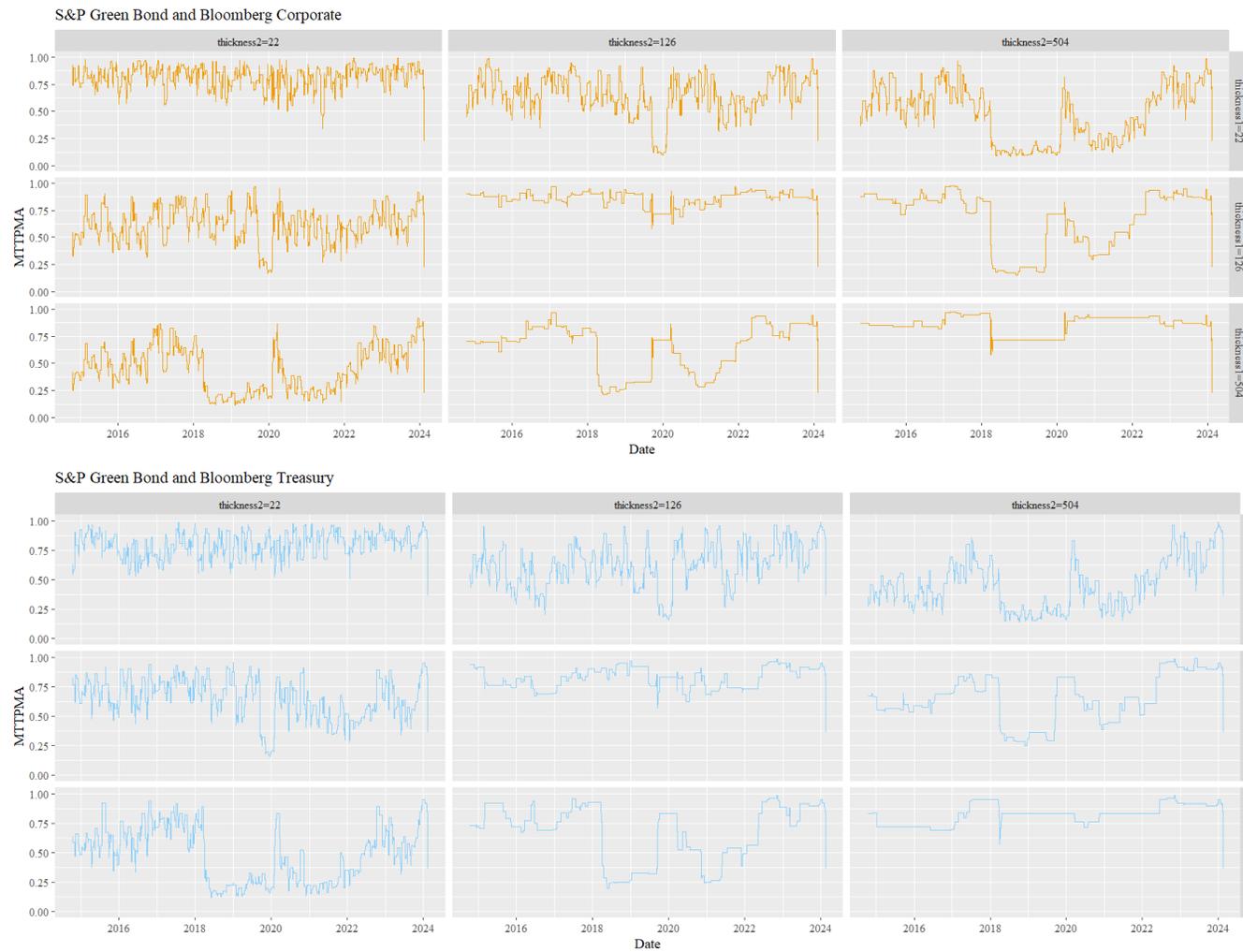


Figure 8: Co-movement of Green Bond returns and Bloomberg Corporate Bond returns (upper panel) as well as Treasury Bond returns (lower panel).

the 2-year overlap rises as early as 2020, earlier than in other comparisons.

In contrast, the co-movement between green bonds and treasury bonds closely mirrors that of aggregate bonds but with slightly lower overlap across all time scales. Treasury bond returns are primarily driven by monetary policy, including central bank interest rate decisions, inflation expectations, and broader macroeconomic conditions, as well as safe-haven flows during periods of market stress. The lower overlap with green bonds suggests that these factors exert less influence on green bond prices. Meanwhile, the stronger co-movement with corporate bonds indicates that green bond dynamics are more closely aligned with corporate credit conditions, liquidity factors, and investor sentiment in the corporate bond market, highlighting a structural link that differentiates green bonds from government securities and underscores their distinct role in fixed-income portfolios. Overall, the results from the cross-scale analysis closely mirror those found in the examination of the relationship between green bond returns and aggregate bond returns.

Finally, we turn to the co-movement between green bond returns and the MSCI Energy Stock Index, as shown in Figure 9 (upper panel). The overall pattern is similar to that observed between green bonds and the MSCI Environment Stock Index, but there are some noteworthy differences. The overlap is generally lower and exhibits a clearer downward trend, particularly evident in the overlap of the 6-month features. For the 2-year features, the downward shift is even more pronounced, with a noticeable drop occurring as early as 2018. This suggests a distinct dynamic between green bonds and the



Figure 9: Co-movement of Green Bond returns and MSCI Energy Stock Index returns (upper panel) and NASDAQ OMX Solar returns (lower panel)

MSCI Energy Stock Index, with greater divergence over time compared to the other indices examined. This is noteworthy insofar as the MSCI Energy Stock Index consists mostly of firms from the oil and gas sector, as the index is dominated by integrated oil companies, exploration and production firms, and oilfield services providers, with relatively limited exposure to renewable or clean energy businesses.

The co-movement between green bond returns and returns from additional specific stock indices varies. Shown in Figure 9 (lower panel) is the co-movement of green bond returns and those of the NASDAQ OMX Solar Index. The overlap of the 1-month features of the data does not vary considerably and is found to be between 0.5 and 0.75. The overlap of both the 6-months-feature and the 2-year-feature of the data is slightly decreasing over time. Otherwise, the co-movement between green bond returns and those of the NASDAQ OMX Water Index is higher, while the co-movement with NASDAQ OMX Transport is lower. The co-movement with NASDAQ OMX Wind Index returns shows a larger degree of time variation, with the overlap fluctuating significantly, even for the 2-year features of the data. Similarly, the co-movement between green bond returns and the NASDAQ OMX Solar Index is characterized by a clear downward trend, adding another layer of complexity to the observed patterns. See Figures 10 and 11 in Appendix A.

To assess the robustness of our analysis, we employ a standard Dynamic Conditional Correlation (DCC)-GARCH framework. The resulting dynamic

correlations, reported in Figures 12 and 13 in Appendix B, broadly confirm the main findings of the Thick Pen Analysis. In particular, green bond returns exhibit stronger dynamic correlation with benchmark bond markets than with equity markets, and correlations increase during the crisis periods of 2022 and 2023. Among equity markets, correlations are highest with environmental stocks, followed by the broad MSCI index, and lowest with the MSCI Energy index.

At the same time, the DCC-GARCH results highlight important differences in what this approach captures. The model primarily reflects short-term correlation dynamics and does not account for co-movement in long-run features of the data, nor does it allow for cross-scale interactions. As a simple proxy for long-term co-movement, we therefore also report rolling-window correlations for a subset of markets in Appendix B; see Figures 14 and 15. These results are broadly consistent with our main findings, though not identical, which is expected given that the Thick Pen analysis captures specific forms of scale-dependent co-movement, as discussed at the end of Section 3.2.

To summarize, one of the key findings of this paper is that crisis periods alter the overlap between green bond returns and other financial returns in a market-specific manner. During the onset of the Ukraine war in 2022, green bonds exhibited markedly stronger co-movement with other bond markets, with aggregate bond returns showing the largest increase, while the COVID-19 episode had little effect on these relationships. By contrast, co-movement

with the broad MSCI equity market weakens during the Ukraine war, but only from 2023 onward, whereas linkages with energy- and environment-focused equity indices remain largely stable. Overall, these patterns indicate that green bond prices are particularly sensitive to monetary policy and inflation dynamics, while their connections to sector-specific information—especially in energy-related equities—remain robust amid heightened geopolitical uncertainty.

## 5 Conclusions

Over the past two decades, the green bond market has expanded rapidly. It primarily serves as a crucial funding mechanism for the transition to a carbon-neutral economy. However, like any emerging asset class, it has also attracted investors seeking diversification. This paper explores the inherent tension between these two roles - sustainable finance and return-oriented investment.

We examine the co-movement between the returns of green bonds and those of various financial markets, both green and conventional, using the Thick Pen Measure of Association (TPMA)([Fryzlewicz & Oh, 2011](#); [Jach, 2017, 2021](#)). This method provides a robust framework for analyzing financial market relationships across multiple time scales. Unlike traditional correlation measures, TPMA smoothes data to minimize noise and short-term volatility, which makes it particularly effective in identifying structural

shifts and evolving dependencies. Its versatility across asset classes allows for the detection of cross-scale interactions that conventional methods might overlook; thus, TPMA is a powerful tool for understanding market dynamics, optimizing portfolio diversification, and assessing financial stability.

Our analysis reveals that the co-movement between green bond returns and other financial markets is both market-specific and time-varying. First, co-movement evolves dynamically over time, with major global events—most notably the Ukraine war—acting as important turning points, although meaningful changes are already visible as early as 2017, well before recent crises. Second, green bond returns exhibit the strongest and most persistent co-movement with benchmark bond markets, suggesting that conventional fixed-income fundamentals such as interest rates, inflation expectations, and credit conditions play a central role in shaping green bond performance. Third, co-movement with stock market returns is generally weaker and, in the case of broad equity indices, shows a declining trend over time, highlighting the distinct pricing dynamics of green bonds relative to equities. Weakest co-movement is found between green bond returns and MSCI Energy Stock Index returns, which consists mostly of oil and gas companies. At the same time, short-term fluctuations in green bond returns remain influenced by longer-term developments in stock markets, particularly during periods of heightened uncertainty such as the COVID-19 outbreak and the Ukraine war, reflecting the role of aggregate risk sentiment and macroeconomic shocks in linking green bonds to the broader financial system.

Our findings contribute to the literature in several ways. They reinforce the evidence of diversification benefits, consistent with studies such as [Karim et al. \(2024\)](#), who highlight green bonds' role in diversification, safe-haven protection, and hedging, as well as the impact of COVID-19 on risk spillovers. However, while their analysis focuses on extreme risk dependence using time-varying copula models and extreme risk spillover analysis, our approach provides a broader perspective on co-movement dynamics across different time scales. Our results are consistent with the literature on climate risk and green investments ([Arfaoui et al., 2024](#)). They indicate that green bond returns are primarily driven by conventional fixed-income factors rather than by broad stock market dynamics. Moreover, co-movement with environmentally focused equity indices remains largely stable over time, while the weakest association is observed with conventional energy sector indices, underscoring the limited influence of fossil-fuel-based equity markets on green bond pricing. Our results are also consistent with [Chatziantoniou et al. \(2022\)](#), who show that market connectedness varies over time and is influenced by economic events. Similarly, [Ren et al. \(2024\)](#) examine the informational efficiency of energy and green markets, with a particular focus on the spillover of inefficiencies, and find that green markets tend to be more independent. Our findings reinforce this notion, which confirms that green bond markets exhibit distinct dynamics.

Our findings also carry important implications for investors seeking to optimize portfolio allocations and for policymakers evaluating green bonds as a

tool for climate finance. At a fundamental level, the green bond market operates much like a conventional bond market, with pricing largely driven by the same macroeconomic and fixed-income factors that shape broader bond markets. This duality is both encouraging and challenging. On the positive side, the bond-like nature of green bonds implies relative price stability, predictable risk–return characteristics, and meaningful diversification benefits, making them well suited for long-term investors and climate-resilient portfolio construction. Their weak and declining co-movement with equity markets further enhances their role as stabilizing assets in diversified portfolios, particularly during periods of equity market stress.

At the same time, the reliance of green bond pricing on overall bond market conditions introduces vulnerabilities. When conventional bond markets face adverse shocks—such as sharp interest rate increases or shifts in inflation expectations—green bonds are likely to be affected as well, limiting their ability to act as a standalone hedge against systemic financial risk. For asset allocators, this highlights the importance of integrating green bonds within broader fixed-income strategies rather than treating them as a distinct asset class insulated from market-wide forces. For regulators and policymakers, our findings suggest that promoting green bond issuance alone may not be sufficient to ensure stable financing for the energy transition. Supporting market depth, liquidity, and resilience—through clear standards, credible certification, and alignment with monetary and fiscal policy—will be crucial to prevent green bonds from becoming overly exposed to cyclical bond mar-

ket sentiment. Ultimately, the effectiveness of green bonds in financing the energy transition depends not only on their environmental objectives but also on how well they are embedded in robust, climate-resilient financial systems.

### **Declaration of generative AI and AI-assisted technologies in the writing process**

During the preparation of this work the authors used chatgpt in order to improve language and readability. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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## **A Appendix A**

Appendix A presents the remaining results.

## **B Appendix B**

Appendix B presents the results of the robustness check.

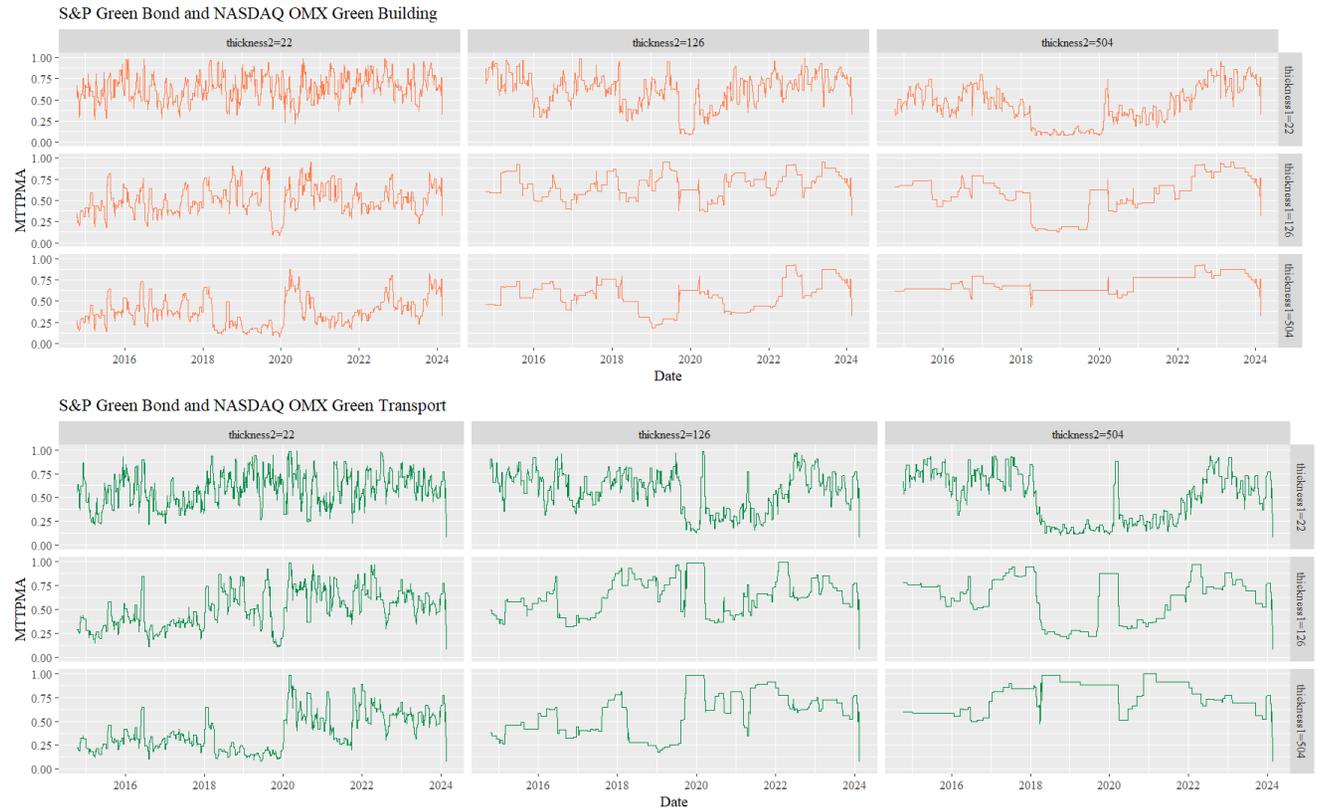


Figure 10: Co-movement of Green Bond returns and NASDAQ OMX Buildings returns (upper panel) and NASDAQ OMX Transport returns (lower panel)



Figure 11: Co-movement of Green Bond returns and NASDAQ OMX Water returns (upper panel) and NASDAQ OMX Wind returns (lower panel)

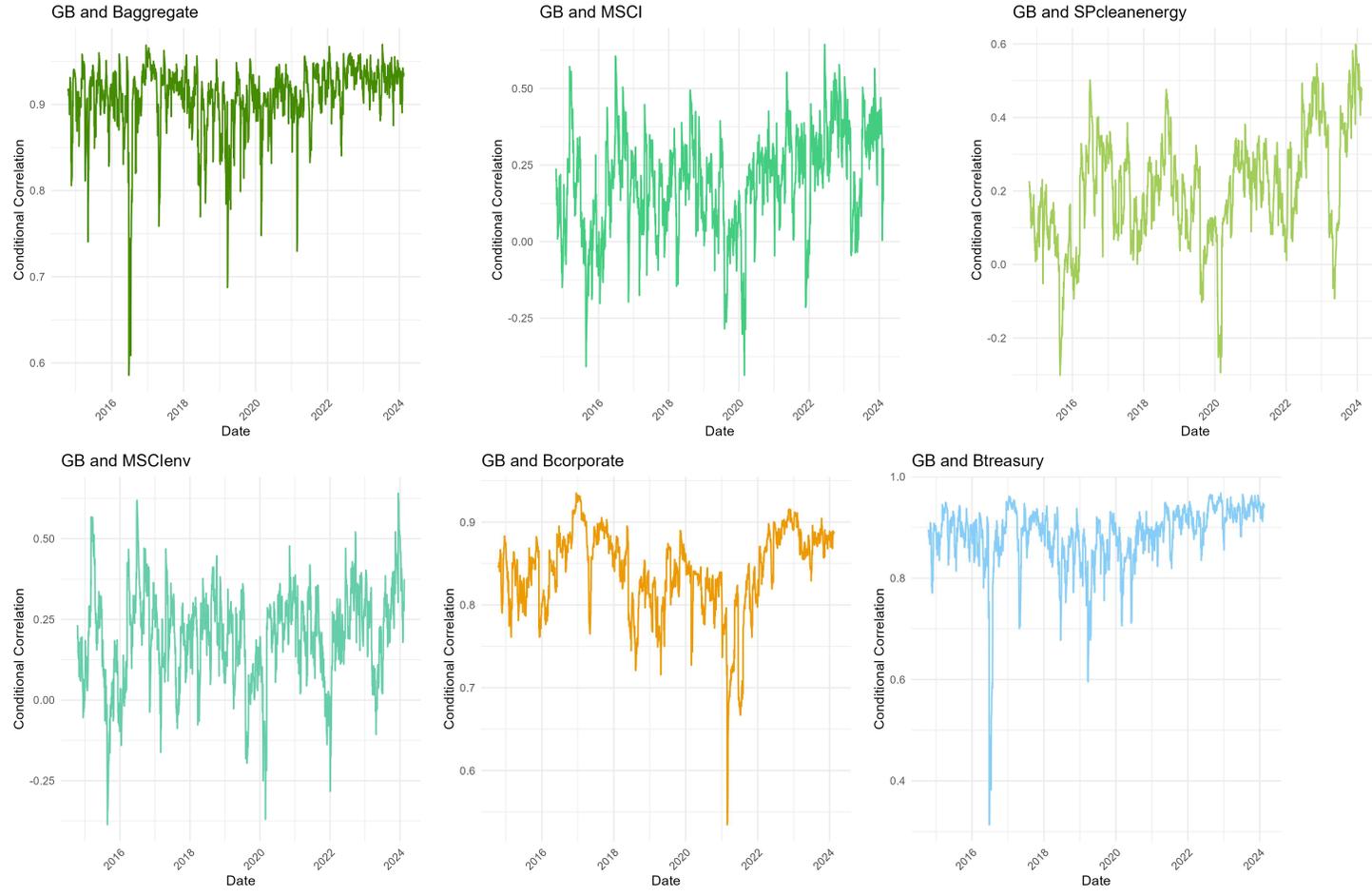


Figure 12: DCC GARCH - Conditional Correlation

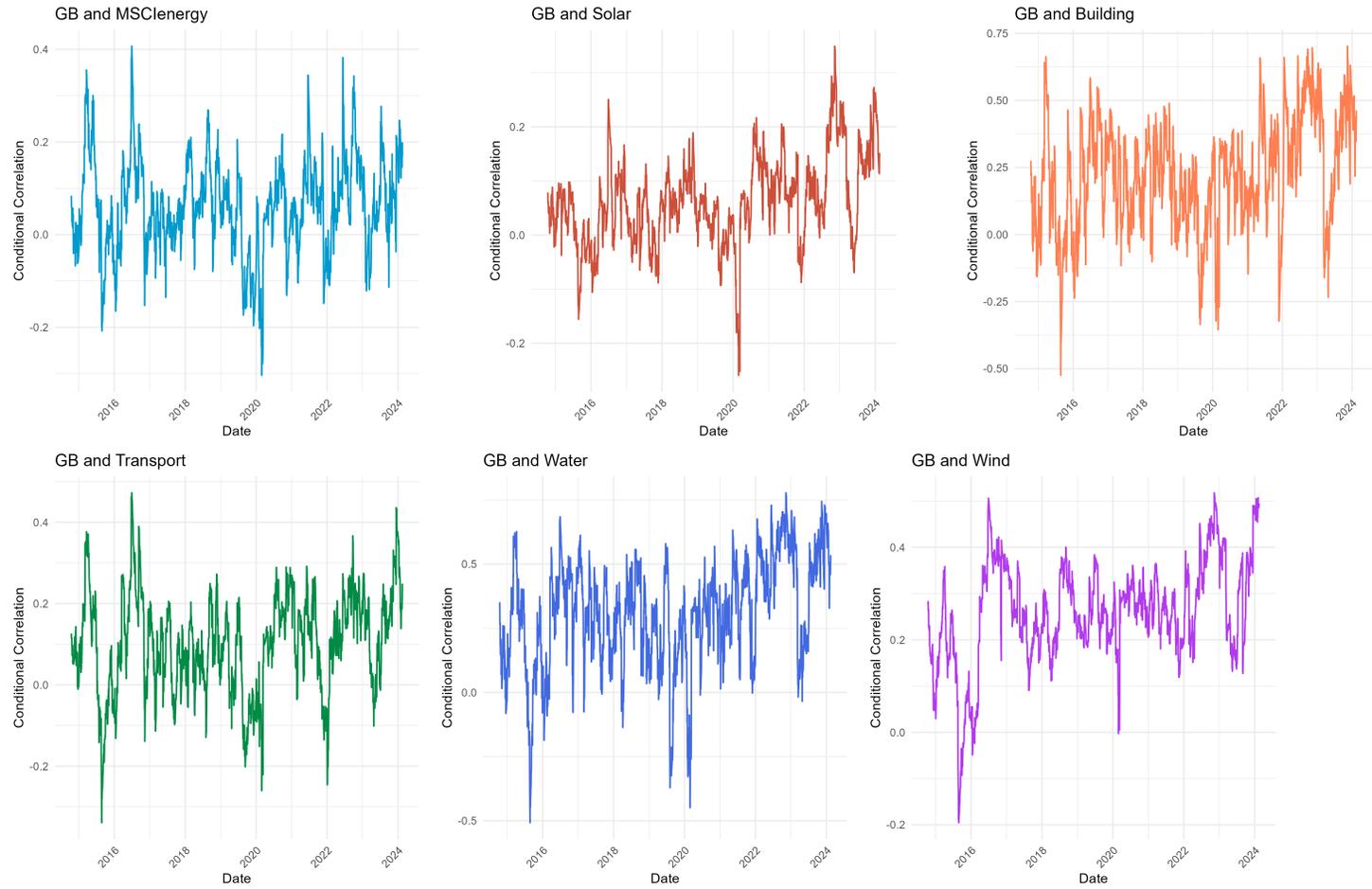


Figure 13: DCC GARCH - Conditional Correlation

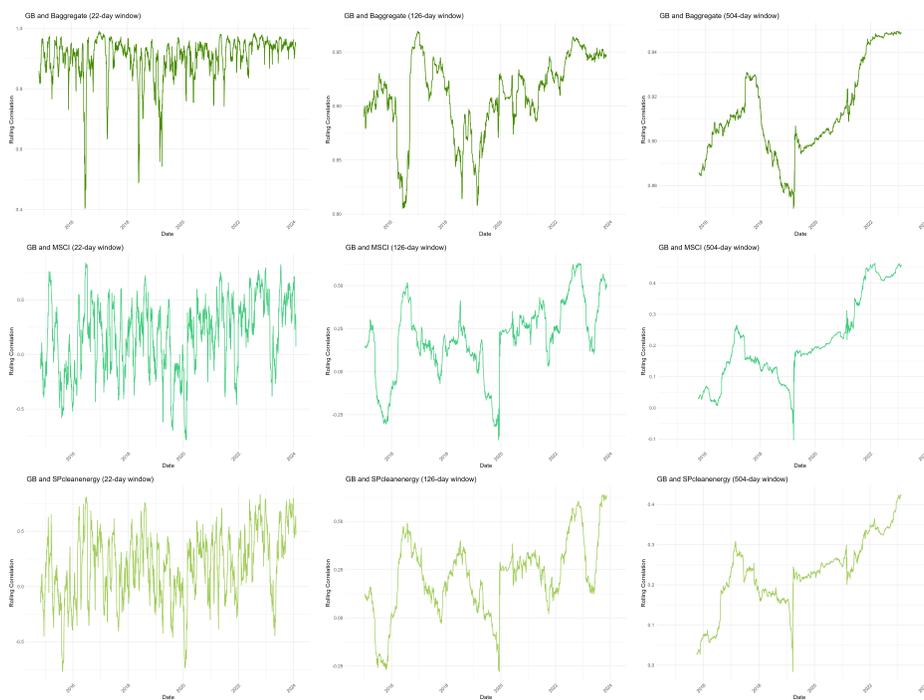


Figure 14: Time-varying Correlation

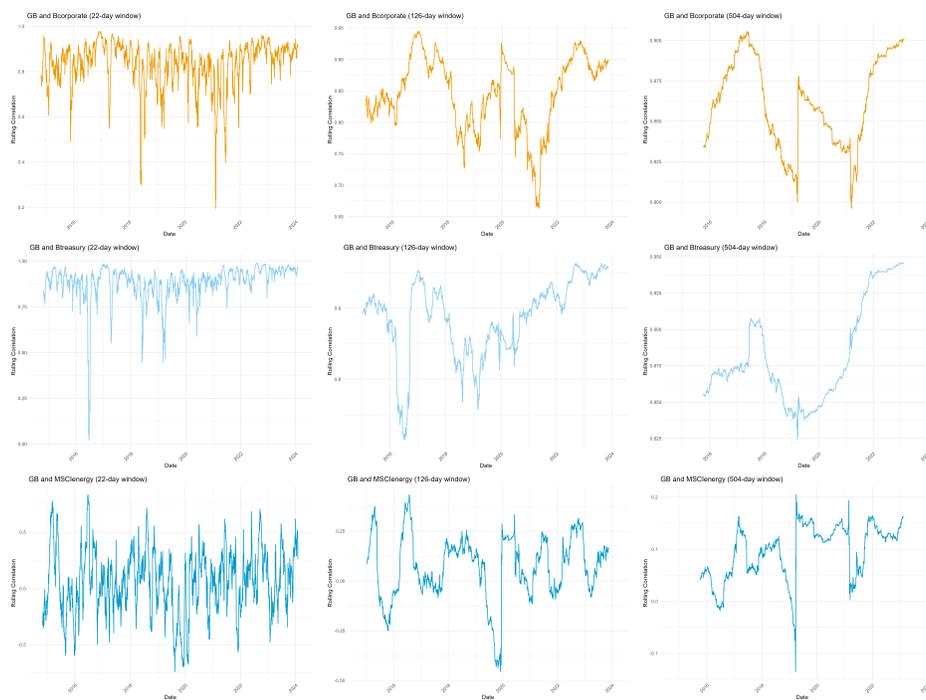


Figure 15: Time-varying Correlation