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# Green Bond Returns and the Dynamics of Green and Conventional Financial Markets: An Analysis Using a Thick Pen

## Abstract

This paper explores the relationship between green bond markets and both green and conventional financial markets, while also evaluating their effectiveness as a climate finance instrument. Using the Thick Pen Measure of Association — a visually interpretable tool for analysing co-movement across different time scales — we identify several key findings. First, the relationship between green bonds and other markets evolves over time, influenced by major events such as COVID-19, the Ukraine war, and earlier structural changes. Second, green bonds show the strongest co-movement with benchmark bond markets, indicating they are driven by similar fundamental factors. In contrast, their connection to stock markets is weaker and, in some cases, declining, reinforcing their potential as a diversification tool. However, short-term movements in the green bond market remain closely linked to the long-term stock market environment, particularly during periods of market stress.

JEL-Codes: C140, C320, C460, G120, Q560.

Keywords: green bonds, financial markets, co-movement, Thick Pen Measure of Association, data science.

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### 1 Introduction

The global shift toward clean energy, coupled with growing concerns about climate change and sustainability, has propelled green investments into the spotlight, capturing the attention of policymakers, investors, and researchers alike. In particular, since the issuance of the first green bond by the European Investment Bank (EIB) in 2007, there has been significant growth in the green bond market. This increasing trend is often referred to as a 'green bond boom' (Morgan Stanley, 2017). The data compiled by Climate Bonds Initiative (2024) clearly highlights this trend: cumulative issuance from 2006 to 2013 remained well below USD 50 billion. In 2017, issuance surged to nearly USD 200 billion, and in 2021, the market saw its strongest year ever, with issuance surpassing USD 1,000 billion. Between 2022 and 2024, issuance has consistently remained above USD 800 billion.

This dramatic growth has not gone unnoticed in the academic literature; for an early and important contribution, see Flammer (2020). There is clearly strong demand for green bonds, driven by investors' growing interest in sustainable investments. These investments are vital, as the transition to a carbon-neutral society requires substantial financial commitments. However, the appeal of green bonds goes beyond environmental concerns. Following the Global Financial Crisis, investors began rethinking their portfolios due to the reduced diversification benefits offered by equity markets. As a result, understanding the relationship between green bonds and other financial markets, both green and conventional, has become increasingly important. Insights into their co-movement can help optimize portfolio allocation and provide valuable perspectives on evaluating green bonds as a key instrument for financing the energy transition.

We investigate return co-movement between the green bond and other, both green and conventional, financial markets using 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)' to provide new insights on the changes in the co-movement dynamics. 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 topic has been explored in a rapidly growing body of academic literature. Among the most recent contributions, Karim, Lucey, Naeem, and Yarovaya (2024) investigate the extreme risk dependence between green bonds and broader financial markets, highlighting the significant diversification benefits that green bonds can offer, along with safe-haven and hedging opportunities. 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.

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). Other studies on the relationship between green bonds and various financial markets include 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.

Our theoretical basis for the integration between green bonds and equity relies on the theoretical link between bonds and the conventional stock market as suggested by Dean, Faff, and Loudon (2010) who find asymmetry in return and volatility spillover between the traditional bond and stock market. In addition to this perspective, our paper is also an evaluation of green bonds as climate finance instruments; see e.g. Flammer (2021) as well as Gronwald and Wadud (2025). Our empirical strategy is motivated by Pham (2021) and Chatziantoniou et al. (2022) who use a cross-quantile dependence framework to investigate price connectedness between green bonds and green equity. While their model is based on a parametric approach, we use a non-parametric approach that is based on the Thick Pen Transform (TPT) method.

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: Section 2 describes both the data and the method used in this paper. Section 3 presents the empirical results and Section 4 offers some concluding remarks.

#### 2 Data and Method

#### 2.1 Data

This study extends the datasets employed by Gronwald and Wadud (2025) and Pham (2021), leveraging a more comprehensive set of financial indices to capture the dynamics of the green bond market within the broader financial domain. Specifically, 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.

Additionally, 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-fueldominated 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.

Recognizing the potential influence of policy uncertainty, this study incorporates 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.

Index	Bloomberg Ticker	Benchmark	Notation
S&P Dow Jones Green Bond TR Index	SPUSGRN	Green bond	GB
NASDAQ OMX Clean Energy-focused Index	GRNCLNFO	Green equity: Clean energy	Cleanenergy
NASDAQ OMX Wind	GRNWIND	Green equity: Wind energy	Wind
NASDAQ OMX Green Building	GRNGB	Green equity: Building	Building
NASDAQ OMX Solar	GRNSOLAR	Green equity: Solar	Solar
NASDAQ OMX Green Transportation	GRNTRN	Green equity: Transportation	Transportation
NASDAQ OMX Global Water	GWATERL	Green equity: Water	Water
MSCI World	MXWO	General stock	MSCI
MSCI World Energy Index	MXWO0EN	Energy stock	MSCIenergy
MSCI Global Environment Index	GEIB	Environment stock	MSCIenv
S&P Global Clean Energy Index	SPGTCED	Clean energy stock	SPcleanenergy
Bloomberg Global Aggregate Corporate	LGCPTRUU	Global bond	Bcorporate
Bloomberg Global Aggregate Treasuries	LGTRTRUU	Global bond	Btreasury
Bloomberg Global Aggregate Index	LEGATRUU	Global bond	Baggregate
US Economic policy uncertainty index	EPU	Policy uncertainty	EPU

Table 1: Description of data

Source: Bloomberg terminal

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.



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

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 onset of the Ukraine war.

Comparing this to other markets, aggregate bond returns (upper right panel) exhibit a very similar pattern, suggesting that the same factors influencing aggregate bond markets also drive green bond prices. The MSCI index (bottom left panel) follows an intriguing trajectory: experiencing heightened volatility in 2015 and 2016, then stabilizing, followed by another increase in



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

2018 and 2019. The COVID shock had a more prolonged effect on the MSCI index, and while volatility in 2022/2023 was higher than in 2021, the relative impact was not as pronounced as in bond markets.

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 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. Notably, 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.

The returns of broader clean energy stock market indices reveal an interesting pattern. Notably, 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.

Figure 3 displays the returns of the remaining niche, specialized stock indices examined in this study, each exhibiting distinct idiosyncratic features. Notably, 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.

#### 2.2 Method

The Thick Pen Transform (TPT) introduced by Fryzlewicz and Oh (2011) was subsequently extended into Thick Pen Measures of Association (TPMA) by the same authors and further refined into Multi-Thickness Thick Pen





Measures of Association (MTTPMA) by Jach (2021).

The methodology involves plotting a given time series  $X = (X_t)_{t=1}^T$ , such as daily returns, on a two-dimensional graph with time on the x-axis and series values on the y-axis. The data points are connected sequentially with pens of varying thickness. By varying the thickness of the pen different data characteristics are highlighted: thinner pens capture high-frequency (shortterm) movements, while thicker pens accentuate lower-frequency (long-term) movements.

Consider a univariate time series X, which may be either stationary or non-stationary. Let  $\mathcal{T}$  denote a set of positive constant thickness parameters, with each  $\tau_i \in \mathcal{T}, i = 1, 2, ..., |\mathcal{T}|$ , where  $(|\mathcal{T}|$  represents the cardinality of  $\mathcal{T}$ ). Here,  $\tau$  signifies one of the elements of  $\mathcal{T}$ , indicating the thickness used to analyze different frequency movements in X, thereby highlighting either short-term or long-term trends.

To apply the Thick Pen Transform (TPT) to X, plot  $X_t$  against t using varying thicknesses of pen  $\tau \in \mathcal{T}$ . This results in two random variables representing the lower  $L_t^{\tau}(X)$  and upper  $U_t^{\tau}(X)$  boundaries of the area covered by the pen, defined by the following:

$$L_t^{\tau}(X) = \min(X_t, X_{t+1}, ..., X_{t+\tau})$$
$$U_t^{\tau}(X) = \max(X_t, X_{t+1}, ..., X_{t+\tau})$$

Following Jach (2021), this study uses a retrospective approach (look-

back), appropriate when observations are available only up to time t.

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

These boundaries extract the feature of X with respect to a varying time scale of  $\tau$ . The TPT thus comprises n pairs of upper and lower boundaries and can be denoted for a set of 2 and  $|\mathcal{T}|$  sequences of length T (in total  $2 \times n \times T$  random variables) by

$$TP_{\mathcal{T}}(X) = \{ (L_t^{\tau}(X), U_t^{\tau}(X))_{t=1}^T \}_{\tau \in \mathcal{T}}$$



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 thick-

nesses 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.

The Thick Pen Measure of Association (TPMA) proposed by Fryzlewicz and Oh (2011) builds upon TPT and quantifies the overlap between the area defined by the TPTs of time series for a given time scale. This time series needs to be standardized, e.g., z-score method, before applying the method. Formally, we have standardised time series of K-th,  $\underline{X} = (X^{(1)}, X^{(2)}, ..., X^{(k)})$ ,  $X^{(k)} = \{X_t^{(k)}\}_{t=1}^T, K = 1, 2, ..., K$ . Additionally, let their respective TPTs be  $TP_{\mathcal{T}}(X^{(1,2,...,K)})$  for a given set of n thickness parameters,  $\mathcal{T} = \tau_1, \tau_2, ..., \tau_n$ . The TPMA between the series, for all t and  $\tau$ , is defined as

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

This measure is bounded in the interval  $\rho_t^{\tau}(X^{(1)}, X^{(2)}) \in (-1, 1]$ . This metric can be easily interpreted in a time-varying manner by observing the overlap between the TPTs. Values close to 1 indicate strong comovement or synchrony, as the areas largely overlap. Negative values indicate a lack of synchrony or the presence of a gap between the series. Notably, independent series may exhibit TPMA values near 1 for large thickness values.<sup>1</sup>. The Multi-Thickness Thick Pen Measure of Association (MTTPMA), further developed by Jach (2021) generalizes TPMA by allowing each series to be

<sup>&</sup>lt;sup>1</sup>For more details, see Jach (2017) and Jach (2021)

transformed with its distinct thickness parameter. This modification allows capturing cross-scale dependencies, which can be denoted as follows

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

The scalar  $\tau$  of Equation (1) is replaced by the vector  $\tau^{(1,2...,k)}$  in Equation (2), enabling each time series to have different thickness, which allows capturing cross-scale dependency between two time series.

### 3 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 begin with the co-movement between green bond returns and Bloomberg Aggregate Bond returns, see Figure 5. The topleft panel of the figure shows that the overlap between the 1-month features of the data fluctuates around 0.75, indicating a strong co-movement. There is some time variation, with the overlap dipping 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, reflecting 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, though the increase in 2022 is clearly visible. These findings suggest that green bond returns and aggregate bond market returns generally move closely together. In other words, 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 MTTPMA 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 strongly related to the broader aggregate bond market environment, particularly during challenging periods such as early 2020 and 2022/2023.

A similar pattern is observed in the overlap between the 2-year features

of green bond returns and the 1-month features of aggregate bond returns (bottom left panel), though 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 notable is the low overlap in 2018, as well as in 2023 and 2024. The latter finding is especially intriguing but can be well explained: green bond markets are more strongly influenced by concerns over inflation shocks and potential central bank responses than the broader stock market.

This divergence becomes even more pronounced when analyzing the 6month 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 positive from a diversification perspective, as it indicates that their price drivers are distinct from those of general equity markets.

The cross-scale overlap reveals interesting patterns also in this case. While the overlap between the 2-year features of green bond returns and the 1month features of MSCI stock returns (bottom-left panel) fluctuates in a



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

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 bonds are influenced not only by the long-term trends in the broader bond market but also by the long-term stock market environment.

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 fluctuates between 0.5 and 0.75, with occasional deviations beyond this range. The overlap reaches its lowest levels in 2017, as well as in 2021 and 2023.

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 analyzing 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. Additionally, the overall degree of overlap remains significantly lower than that observed between the 2-year features of green bond returns and aggregate bond returns.

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 to previous cases. However, one key distinction is the relative stability of the overlap over time, with only minor fluctuations. The overlap is slightly lower in 2017 and noticeably higher from 2022 to 2024. This



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).

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. Notably, this is higher than the overlap observed between green bonds and aggregate bonds, and it also exhibits less variation over time.

A similar pattern holds for the 6-month and 2-year features, where the overlap remains higher than in the case of aggregate bonds. Interestingly, the 2-year overlap shifts upward as early as 2020, rather than in 2022, as seen in other cases. However, the cross-scale overlap remains low between



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

2018 and 2022, an aspect that warrants further discussion.

For treasury bonds, the results closely resemble those for aggregate bonds, though with slightly lower overlap across all time scales. The overall pattern remains remarkably similar. Since treasury bond returns are heavily influenced by monetary policy, the lower overlap with green bonds suggests that green bond prices are not affected by monetary policy to the same extent—though they are still influenced to a considerable degree. In contrast, the higher co-movement with corporate bonds highlights a key difference, suggesting that corporate bond dynamics align more closely with green bond markets than treasury bonds do. This distinction is particularly interesting and worth further exploration.

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 notable 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 MSCI Energy Stock Index, with greater



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

divergence over time compared to the other indices examined.

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.

#### 4 Conclusions

Over the past two decades, the green bond market has expanded rapidly, primarily serving 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 smooths data to minimize noise and short-term volatility, making 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, making TPMA 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 varies across markets and over time. First, this co-movement evolves dynamically, with major events like COVID-19 and the Ukraine war acting as key drivers, though notable shifts also emerge as early as 2017. Second, green bond returns exhibit the strongest co-movement with benchmark bond markets, indicating that broader bond market fundamentals also shape green bond performance. Third, the co-movement with stock market returns is generally weaker and, in some cases, shows a declining trend, underscoring green bonds' distinct market behavior. However, shortterm fluctuations in the green bond market remain closely linked to the long-term stock market environment, particularly during periods of market stress, such as the COVID-19 outbreak and the Ukraine war.

Our findings contribute to the literature in several ways. They reinforce the evidence of diversification benefits, aligning with 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 also align 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 information efficiency of energy and green markets, particularly the spillover of inefficiencies, and find that green markets tend to be more independent. Our findings reinforce this notion, confirming that green bond markets exhibit distinct dynamics.

Our findings have important implications for both investors optimizing portfolio allocations and policymakers assessing green bonds as a climate finance tool. At its core, the green bond market operates much like any other bond market — its pricing is driven by the same fundamental factors that influence broader fixed-income markets. This is both promising and problematic. On the one hand, green bonds behaving like conventional bonds provide stability and make them a predictable investment. Their diversification benefits also enhance their attractiveness. However, the risk lies in their dependence on overall bond market sentiment — if traditional bonds fall out of favour, green bonds may suffer the same fate. Moreover, if investors find alternative diversification strategies, interest in green bonds could wane. Given the massive funding required for the energy transition, the long-term viability of green bonds depends not just on their own market dynamics but also on broader financial trends and investor preferences.

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## A Appendix

This Appendix presents the remaining results.



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)