Anatomy of Municipal Green Bond Yield Spreads

Mohammad Hadi Sehatpour[a], Marta Campi[b], Christina S. Nikitopoulos[a,*], Gareth W. Peters[c], Kylie-Anne Richards[a,d,**]

[a] *University of Technology Sydney, Finance Discipline Group, UTS Business School, PO Box 123 Broadway NSW 2007, Australia*

[b] *Institut Pasteur, Université Paris Cité, Inserm, Institut de l'Audition, IHU reConnect, F-75012 Paris, France*

[c] *University of California Santa Barbara, Department of Statistics and Applied Probability, Santa Barbara CA 93106-3110, USA*

[d] *Future Fund Management Agency, Australia's Sovereign Wealth Fund, Locked Bag 20010 Melbourne VIC 3001, Australia*

Abstract

Exploring the attributes of the rapidly evolving green bond market is crucial for directing capital towards projects that mitigate climate risks and facilitate adaptation to environmental changes. We propose novel approaches to compute green bond spreads based on yields to maturity and their term structure. Based on California's green municipal bond market, we find that these two types of green bond spread are on average positive and disparate but reach negative territories and converge after 2022. Using Association Rule Learning, we find that positive tenor-specific spreads are associated with tax status, callability, pricing strategy, and maturity, while negative spread associations are more complex. Yield curve spreads tend to relate to maturity-related attributes. Sector-specific differences in credit ratings, issue sizes, and use of proceeds have also been identified. The distinctive spread structuring attributes highlight the dynamic and heterogeneous nature of green bonds and offer practical insights for green bond screening practice.

Keywords: green bonds, municipal bonds, yield to maturity, yield term structure, use of proceeds

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*Corresponding author christina.nikitopoulos@uts.edu.au Authors alphabetical after first author Ph.D. candidate. A contributions section is included.

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1. Introduction

The issuance of green bonds has been steadily increasing over the years. As of mid-2024, the global issuance of green bonds reached a record $3.2 trillion, which represents a 14% increase from the previous year. This surge is reflective of a wider trend, with the total volume of green, social, sustainability and sustainability-linked debt (GSS +) reaching $5.1 trillion by mid-2024 (CBI, 2023). However, this significant growth of the green bond market has not been done homogeneously. Initially, short-term bonds were issued due to uncertainty and limited demand. Over time, issuances expanded to longer maturities, particularly as major state-based entities joined the market. Recently, municipal issuers focusing on intermediate-term structures have become more prominent, covering a broader range of projects under the "use of proceeds" (UOPs) (Doran and Tanner, 2019; OECD, 2017). Green UOP is a distinct feature of green bonds (compared to conventional bonds) and refers to the explicit allocation of funds raised from a green bond that are expected to fund green-related projects, such as renewable energy, energy efficiency, sustainable water management, and biodiversity conservation.[1] Furthermore, the current demand for green bonds far exceeds their supply, with these constraints arguably stemming from supply issues, as most issuances have been oversubscribed (Brennan and MacLean, 2018). Thus, challenges such as the supply–demand imbalance, insufficient liquidity in secondary markets, and the underdeveloped yield curve for green bonds, leading to a lack of instruments across various tenors,[2] underscore the market's immaturity and the hurdles that must be overcome for its maturation (Shinde, 2021; OECD, 2017). Moreover, current economic conditions, characterized by higher interest rates and inflation, have increased the costs associated with issuing green bonds. This has resulted in a slowdown in the growth of new issuances, as issuers face increased capital expenditure and financing costs, further exacerbating the supply-demand imbalance.[3]

[1] This feature is often included in the issuance prospectus and may provide specific details about the project, environmental impact reports, and second- or third-party assurances. However, it can sometimes be vague. These details influence green index ratings and listings. Currently, specific mandates regarding the use of raised capital have not been legally enshrined as protections in the form of hard green covenants.

[2] While some green bonds now price on or inside their yield curves, the market is not yet as robust as for conventional bonds. This underdevelopment can make it challenging to accurately price green bonds and assess their performance relative to conventional bonds.

[3] See, https://think.ing.com/articles/global-esg-bond-supply-outlook-2024-slowing-down/

As the green bond market expands, investors need to be equipped with the tools and understanding necessary to navigate the complexities of these markets. In light of the unique green attributes embedded in these financial instruments, the performance of green bonds relative to conventional bonds, captured by their spread, attracts significant attention from academics, industries, and policy makers. The spread serves as a critical indicator that can provide information on investor sentiment, risk assessment, and issuer behavior (Fang et al., 2023). In conventional bonds, the risk premium captures information related to structuring, time to maturity, and default risk, while measures of risk premium in green bonds may also reflect the effectiveness of green UOPs over long time periods and green defaults. Green bond spread also mirrors investor demand for environmentally conscious investments and the efficacy of policy interventions to enhance the attractiveness and effectiveness of green bonds, thus informing investment strategies and regulatory frameworks.[4]

Empirical studies on green bond spreads face several critical limitations. First, most studies analyse the greenium – the price premium associated with green bonds – which often offers only a short-term perspective and overlooks deeper market conditions, risk factors, and structuring attributes of green bond spreads (Karpf and Mandel, 2018; Partridge and Medda, 2018). Furthermore, the widespread use of the bond matching design, where spreads are constructed by comparing bond prices between green and conventional bonds, is hindered by liquidity constraints, a limited pool of comparable bonds, and short sample periods (Bhanot et al., 2022; Zerbib, 2019). Finally, studies may focus on specific sectors or use-of-proceeds categories, which limits the generalizability of their conclusions (Bhanot et al. (2022)).

To address these limitations, we propose a novel approach for calculating green bond spreads based on yields to maturity (YTM) and their term structure. We present the computation of two types of "green bond-specific" non-parametric spreads, a tenor-specific approach based on YTM and a yield curve approach based on the term structure of YTM. Using daily data from California municipal green bonds between 2020 and 2023, we calcu-

[4]Policymakers, including regulatory authorities, government agencies, international organizations, central banks, legislative bodies, and environmental agencies, play a crucial role in the green bond market by setting standards, providing market incentives, mitigating risks, and encouraging transparency. They create and enforce regulations that ensure that the proceeds from green bonds are used for genuinely sustainable projects, thus making these bonds more attractive to investors.

lated the two green bond spread measures, capturing the spread of green bonds relative to the U.S. risk-free rate, represented by the U.S. Treasury par curve. California's leadership in environmental policy and being the U.S. state with the highest volume of green bonds and a distinct tax system and market design make it a reflective laboratory for investigating the structuring attributes of green bond markets (Chiang, 2023). We find that these two types of green bond yields are on average positive and disparate in the early years but become negative and converge after 2022.

The economic importance of such spreads lies in the identification of structuring attributes associated with YTM spreads and their term structure to facilitate green bond screening practices and to offer decision-making tools to investors and bond issuers (Lombardi Netto et al., 2021). A screening process that identifies relevant structuring attributes can guide investors in constructing optimal green bond portfolios tailored to their specific investment strategies and risk-return preferences. From an issuer's perspective, green bond screening offers crucial insights into the financial setting of sustainable finance and helps them to strategically position their offerings and re-evaluate their cost of capital (Zhang et al., 2021). In addition to optimizing cost, green bonds allow issuers to enhance their reputation and attract a wider base of socially responsible investors. However, in the absence of clear and established screening methodologies, the selection criteria remain an open question. To inform municipal green bond screening criteria, we employ a machine learning technique, namely Association rule learning (ARL), to address five research questions: a) identify the primary structuring attributes associated with positive and negative spreads; b) determine the attributes associated with extreme positive and negative spreads; c) assess the consistency of spread attributes over time; d) measure the impact of nested and conditional associations in spread attributes, including UOP, tax status, and callability; and e) distinguish the attributes reflecting information from the term structure of the spreads.

Regarding the structuring attributes associated with positive spreads (based on YTM and their term structure), we find that classical attributes such as tax status and pricing strategy are important, as well as self-reported green status. Negative spreads are the result of more complex interactions, including spread and yield on issuance, callability, and maturity. Examining extreme spreads highlights the importance of tax status and callability, with additional attributes such as rating, yield, and maturity playing significant roles. Regarding the temporal consistency of these rules, we find that the tax status and pricing strategy remain stable attributes in explaining the positive spread, while other attributes exhibit varying degrees of consistency over time. In addition, yield curve spreads are strongly associated with duration, maturity, and callability. The distinct attributes of these spreads highlight the dynamic and diverse nature of green bond spreads.

After conditioning on aspects of the green municipal bond, our findings indicate that high-maturity and callable tax-exempt bonds, especially those issued at a premium, tend to have positive spreads. Federally taxable green bonds, particularly when issued at par, also exhibit positive spreads. Conversely, non-callable bonds, those issued at a premium, or with low maturities tend to have negative spreads, especially in federally taxable bonds. Higher coupon rates emerge as a significant structuring property contributing to negative spreads, particularly in federally taxable bonds. Sector-specific differences in credit ratings, issue sizes, and use of proceeds have been identified that can inform green bond portfolio diversification strategies. For instance, the Power sector associates with self-reported bonds, higher credit ratings, larger issue sizes, and specific UOPs related to electricity generation. Although some of these attributes have been identified in previous studies, including Bhanot et al. (2022); Baker et al. (2022); Partridge and Medda (2018), this study offers a comprehensive assessment of their interactions and associations with the sign and magnitude of green bond spreads and how such associations have evolved as the green bond market grows.

We make two key contributions to research dedicated to green bond markets. Firstly, we introduce "green bond-specific" spread measures based on YTM to address the limitations of the literature. Existing studies focusing on the spreads (or premium) of green bonds use the classical notion of matching design to identify conventional bonds with characteristics similar to the green bond to construct the spread (Bhanot et al., 2022; Chang et al., 2024; Larcker and Watts, 2020; Partridge and Medda, 2020; Kapraun et al., 2021; Bour, 2019; Hachenberg and Schiereck, 2018; Zerbib, 2019). This matching approach has multiple limitations. Relying solely on market prices, particularly for over-the-counter (OTC) instruments with limited trading activity, may not provide representative data for spread calculations. The decentralized nature of OTC markets often leads to illiquidity, where infrequent trading results in sparse price data, further complicating accurate spread assessment. The challenge of matching highly liquid bonds with less liquid ones also questions the validity of comparing them solely on price levels (Febi et al., 2018). In addition, due to the limited number of matched bonds (Caramichael and Rapp, 2024), aspects such as time frames, UOPs, and issuer sectors may be constrained. These limitations can lead to an incomplete understanding of the green bond market and introduce a selection bias toward matched bond groups.

Our proposed bond-specific spreads, based on YTM and their term structures, avoid grouping green muni bonds with dissimilar non-green muni alternatives. This is the first study to compute and study spreads that embed information from the term structure of green markets. Considering YTM instead of prices, more reliable spread measures are ensured that capture market dynamics over time. To calculate the spread, we compare each bond with a synthetic reference bond that reflects the structural specifications of the green bond, rather than comparing the green bond curve to a general reference curve. Additionally, we utilize single points and information across the term structure of the green bonds to price them, employing distinct approaches. Therefore, our method is informative and reliable for screening purposes, as it ensures that we obtain spreads specific to each green bond, rather than spreads based on aggregated or bond matching approaches.

Secondly, we offer a comprehensive screening analysis of attributes associated with the green bond market in California, which can be easily extended to other state municipal bond markets, development green bond markets, and corporate green bond markets. This analysis delves into structuring attributes such as market dynamics, tax status, pricing mechanisms, and UOP, which have never been considered before in the literature from a screening perspective for investors and issuers. The design of such financial instruments is still surrounded by high uncertainty, as there is no common understanding of their direct and indirect impacts on the actual economy, financial, and carbon markets ((Monasterolo and Raberto, 2018)). Although more attention has been paid to corporate green bond research, municipal green bond research is gaining popularity. Bhanot et al. (2022); Partridge and Medda (2020) find evidence for a statistically significant green premium in the secondary municipal bond market, but not in the primary market, as green bond issuance can cause a drop in the overall yield curve (green halo effect Falch-Monsen and Linnestad (2024)).

According to Baker et al. (2022), green bonds typically trade at a slight premium of a few basis points compared to similar conventional bonds. Karpf and Mandel (2018) conclude that while green municipal bonds were initially traded at discounted prices and higher yields according to expectations based on their credit ratings, this trend has reversed in recent years as the credit quality of such bonds has improved, resulting in a positive premium. Larcker and Watts (2020) though find a negligible premium in municipal green bonds and Chang et al. (2024); Larcker and Watts (2020) state that green bonds, on average, are not traded at a premium compared to identical conventional bonds. Beyond the evident discrepancy in the results that can be attributed to the methodology and associated limitations, our aim is to offer a comprehensive assessment of structural attribute associations in the green municipal bond markets to inform screening practice.

This study provides critical insights for both investors and issuers in the green municipal bond market. Our findings indicate a downward trend in green bond spreads, reaching negative levels after 2022. This shift reflects evolving perceptions of green credit risk, which, unlike traditional credit risk, is influenced by the complexity of funded projects and their alignment with green labels and indices (Karpf and Mandel (2018)). From an investor's perspective, there is a need for a strategic shift to balance risk and return while supporting sustainability goals, particularly given the distinct financial performance of green bonds compared to conventional bonds. Factors such as tax status and pricing strategies present potential opportunities, but tax implications must be carefully considered. Green bonds also offer diversification benefits that extend beyond traditional approaches (such as sector diversification), as they align with broader environmental goals. For issuers, the results emphasize the importance of structuring green bond offerings to attract investors. Key attributes such as maturity, callability, and tax status significantly influence the spread dynamics, as noted in Bhanot et al. (2022); Baker et al. (2022); Partridge and Medda (2018). By better understanding investor preferences, issuers can design bonds with favorable attributes that secure more competitive pricing and diversify their debt portfolios (Zerbib, 2019).

The remainder of the paper is organized as follows. Section 2 explains the construction of two novel green bond yield spreads, the ARL methods, and the data. The calculation of the green bond yield spreads of the California green municipal bond market and the required data partitioning are detailed in Section 3. Section 4 presents the structuring attribute associations of the green bond spreads. Section 5 discusses the interpretations and financial implications of the findings, and Section 6 concludes.

2. Experimental design, methods and data

In this section, we describe the construction of green bond spreads based on YTM and their term structure, the experimental design, and how the research questions are addressed using the machine learning approach ARL. Finally, we provide the data description.

2.1. Construction of the green bonds spreads

We address crucial challenges in the green bond literature by evaluating the spread of green bond markets based on YTM. This alternative strategy improves valuation stability, especially in the context of illiquidity and OTC pricing complexities. Yield incorporates the comprehensive return of the bond, accounting for interest payments and the impact of purchasing at a discount or premium to par. Using yield for re-evaluation facilitates a straightforward comparison across diverse bonds, irrespective of their price, maturity, or coupon rate. Based on the Bloomberg's Yield and Spread Analysis instructions, they offer a standardized framework for calculating bond yields. Their advanced algorithms account for key factors such as market data, interest rates, and issuer credit quality. This approach helps mitigate the potential inaccuracies in market prices often seen in the illiquid and OTC markets, ensuring that the computed yields are aligned with industry standards. Recalculating bond values using YTMs addresses potential inaccuracies in market prices and ensures alignment with industry standards.

In particular, we convert all bonds to synthetic zero-coupon equivalent YTM for spread analysis. We call these rates synthetic because they are not traded in the market. These zero-coupon instruments are constructed to replicate the behavior of the green and reference bonds, allowing for precise and consistent comparisons. Converting these bonds and rates to equivalent zero-coupon bonds also ensures consistency in rate and yield comparisons. Furthermore, using zero-coupon bonds simplifies the spread calculations, making them easier to interpret. Given the sparse availability of green bonds with varying rates, the current structure of the green bond market benefits from this conversion, enabling better analysis and understanding of green bond spreads relative to market conditions. Moreover, using zero-coupon bond equivalents facilitate enhanced comparability to reference curves, which are typically in zero-coupon bond forms, ensuring accurate assessment of green bond performance and yields relative to other bonds. Thus, this conversion facilitates like-for-like comparisons on a per bond basis and offers an adaptive perspective on the bond's value based on prevailing market conditions and expectations.

We evaluate green bond spreads using YTM through two approaches: a tenor-specific method and a term structure yield curve method. These methods apply various discounting factors to green bonds' cash flows, resulting in green and reference equivalent synthetic Zero-Coupon Bond Yield to Maturity (ZCBYTM). The green equivalent ZCBYTM is then compared with the corresponding reference yields to compute the yield spread. The spread is computed as a non-parametric spread using two time series approaches: a tenor-specific approach and a term structure yield curve approach. These non-parametric spreads are calculated for each individual bond across the dataset on a daily basis.

2.1.1. Tenor-specific time series approach: Green bond spreads based on YTM

To compute the green and reference equivalent ZCBYTMs using the tenor-specific approach, we employ the observed daily YTM of green bonds and a risk-free reference yield, such as the U.S. Treasury par yield, to discount the respective cash flows of the bonds. More specifically, we compute the value of a green bond i by using the YTM of this green bond to discount its cash flows. Thus, all the cash flows of a green bond are discounted by the same fixed rate – its YTM. The value of this bond is then used to compute the equivalent green ZCBYTM. The corresponding reference rate from a risk-free yield curve is selected, so it matches the tenor of the green bond i. We use this reference rate as the fixed rate to discount the (same) cash flows to determine the equivalent risk-free ZCBYTM. The difference between green ZCBYTM and risk-free ZCBYTM determines the spread of green bond i.

- **Green Equivalent ZCBYTMs**

  We consider green bond i at time t with coupon amount C_i, face value (par amount) FV_i, coupon frequency m_i, and annualized $YTM^G_{i,t}$, which has payments in $\hat{N}$ periods from first issuance over the entire term of the bond and in N periods according to the remaining time to maturity. As we propose a dynamic approach on a daily basis, we define $\tau_{i,n}$ representing the remaining year fraction to the n^{th} payment at time t for bond i as follows:

$$\tau_{i,n} := \max\left\{n - \frac{t}{(365/m_i)}, 0\right\}. \tag{1}$$

We also define the indicator function as follows:

$$\mathbb{I}(\tau_{i,n}) := \begin{cases} 1, & \text{if } \tau_{i,n} > 0, \\ 0, & \text{otherwise.} \end{cases} \tag{2}$$

When $\tau_{i,n}$ reaches zero, it signifies that we have either reached or exceeded the coupon payment date for coupon i. At this point, the indicator function will be employed to exclude previously paid coupons from the calculation.

Thus, we calculate equivalent green ZCBYTMs at time t for bond i, denoted as $YTM_{i,t}^{(GZCB),1}$ according to the following steps:

1. Calculate the present value of bond i at time t denoted as $P_{i,t}$ as follows:

$$P_{i,t} = \sum_{n=1}^{N} \frac{C_i \mathbb{I}(\tau_{i,n})}{(1 + YTM_{i,t}^{(G)})^{\tau_{i,n}}} + \frac{FV_i}{(1 + YTM_{i,t}^{(G)})^{\tau_{i,N}}}. \tag{3}$$

2. Define an equivalent zero-coupon bond, characterized by a face value denoted as $\widetilde{FV}$. The face value of the equivalent zero coupon bond i is defined as follows:

$$\widetilde{FV_i} := \max\left\{FV_i, FV_i + C_i\right\}. \tag{4}$$

   $\widetilde{FV}$ is adjusted for bonds that pay both a coupon and par amount on the maturity date. This adjustment is important for bonds where the final coupon is paid at maturity, as it ensures that the equivalent zero-coupon bond properly accounts for the entire cash flow structure. It is defined as the maximum of the original bond's FV or $FV + C$ if there's a coupon on the last day. Subsequently the present value of the equivalent zero coupon bond i at time t, $P_{i,t}^{ZCB}$ is defined as:

$$P_{i,t}^{ZCB} = \frac{\widetilde{FV_i}}{(1 + YTM_{i,t}^{(GZCB),1})^{\tau_{i,N}}}. \tag{5}$$

3. Equate $P_{i,t}$ to $P_{i,t}^{ZCB}$ and rearranging, we can obtain $YTM_{i,t}^{(GZCB),1}$ as follows :

$$\frac{\widetilde{FV}_i}{(1+YTM_{i,t}^{(GZCB),1})^{\tau_{i,N}}} = \sum_{n=1}^{N} \frac{C_i \mathbb{I}(\tau_{i,n})}{(1+YTM_{i,t}^{(G)})^{\tau_{i,n}}} + \frac{FV_i}{(1+YTM_{i,t}^{(G)})^{\tau_{i,N}}}, \tag{6}$$

$$YTM_{i,t}^{(GZCB),1} = \left[\frac{1}{\widetilde{FV}_i}\left(\sum_{n=1}^{N} \frac{C_i \mathbb{I}(\tau_{i,n})}{(1+YTM_{i,t}^{(G)})^{\tau_{i,n}}} + \frac{FV_i}{(1+YTM_{i,t}^{(G)})^{\tau_{i,N}}}\right)\right]^{-\frac{1}{\tau_{i,N}}} - 1. \tag{7}$$

- **Reference equivalent ZCBYTM**

  We compute a reference equivalent ZCBYTM rate, denoted as $YTM_{i,t}^{(RZCB),1}$, using a reference risk-free rate. Discounting rates are derived from the fitted spline curves of annual reference rates at time t, based on the same tenor used in the green ZCBYTM calculation. These rates are applied similarly to the previous stage, discounting the associated cash flows as follows:

$$YTM_{i,t}^{(RZCB),1} = \left[\frac{1}{\widetilde{FV}_i}\left(\sum_{n=1}^{N} \frac{C_i \mathbb{I}(\tau_{i,n})}{(1+r_t^{(Tr)}(\tau_{i,N}))^{\tau_{i,n}}} + \frac{FV_i}{(1+r_t^{(Tr)}(\tau_{i,N}))^{\tau_{i,N}}}\right)\right]^{-\frac{1}{\tau_{i,N}}} - 1, \tag{8}$$

  where $r_t^{(Tr)}(\tau_{i,N})$ is the corresponding reference rate for $\tau_{i,N}$ year(s) maturity bond at time t and $YTM_{i,t}^{(RZCB),1}$ is the reference equivalent ZCBYTM rate of the bond i at time t corresponding to the discount factor $r_t^{(Tr)}(\tau_{i,N})$.

- **Spread Calculation**

  Once the $YTM_{i,t}^{(GZCB),1}$ and $YTM_{i,t}^{(RZCB),1}$ have been determined, we can determine the daily spread based on YTM. We define the non-parametric $S_{i,t}^{1}$ as follows: [5]

$$S_{i,t}^{1} := YTM_{i,t}^{(GZCB),1} - YTM_{i,t}^{(RZCB),1}. \tag{9}$$

[5] We opt to define a YTMZCB corresponding to the reference rate $r_t^{(Tr)}(\tau_{i,N})$, as opposed to a direct comparison of this rate ($r_t^{(Tr)}(\tau_{i,N})$) with the $YTM_{i,t}^{(RZCB),1}$. This approach allows us to capture specific bond characteristics, including coupon rate, coupon frequency, and maturity, through defining a reference rate. From a mathematical standpoint, the rationale lies in dealing with a non-linear (hyperbolic) transformation of rates. It is important to note that the input rate ($r_t^{(Tr)}(\tau_{i,N})$) undergoes a non-linear transformation, and this discrepancy with $YTM_{i,t}^{(RZCB),1}$ becomes more pronounced, especially as the maturity period extends.

Essentially, the tenor-specific approach uses a single matching tenor point on the green and reference yield curves and compares a time series of green ZCBYTM with a time series of risk-free ZCBYTM at the same tenor point to obtain the spread of the green bond i. We repeat this method for all green bonds on day t, and consequently compute the spread for all available green bonds on this day.

2.1.2. Yield curve time series approach: Green bond spread based on the YTM term structure

In the yield curve time series approach, discount factors vary across different terms and are computed based on the respective tenors, using the fitted yield curves of both green and risk-free reference yield. This approach involves using a comprehensive set of data points across the term structure of the yield curve. It allows us to make a curve-to-curve comparison on the same day. Thus, incorporating the term structure of yield curves allows for varying discount rates based on the tenors of cash flows. It also provides a detailed and dynamic valuation by considering the yield curve's shape and fluctuations, potentially offering an active reflection of market conditions and interest rate movements. As a result, it can capture term-specific risk and return expectations.

- **Green equivalent ZCBYTM**

  We employ an alternative method to compute the green spot rates and, consequently, the equivalent ZCBYTM. This method involves the following steps:

  1. Grouping bonds: To enhance comparability and construct yield curves for green bonds with similar specifications, we classify them into distinct taxonomies based on their specifications.
  2. Curve construction via non-parametric bootstrapping: For each group, we construct a spline bootstrapped green curve daily, using their given daily YTM.
  3. Spot rate determination: Using this green yield curve, we calculate the corresponding green spot rates necessary to discount each cash flow of the bond, and the equivalent green ZCBYTM for the second approach denoted as $YTM_{i,t}^{(GZCB),2}$ can be calculated as follows:

$$YTM_{i,t}^{(GZCB),2} = \left[\frac{1}{\widetilde{FV_i}} \left(\sum_{n=1}^{\hat{N}} \frac{C_i \mathbb{I}(\tau_{i,n})}{(1 + (\frac{r_t^{(G)}(\tau_{i,n})}{m_i}))^n} + \frac{FV_i}{(1 + (\frac{r_t^{(G)}(\tau_{i,N})}{m_i}))^N} \right) \right]^{-\frac{1}{N}} - 1, \tag{10}$$

where $r_t^{(G)}(\tau_{i,n})$ and $r_t^{(G)}(\tau_{i,N})$ represent yields extracted from bootstrapped green yield curves corresponding to their respective terms $\tau_{i,n}$ and $\tau_{i,N}$ at time t for bond i, and $n, \ldots, N$ are the corresponding tenors considered at time t.

- **Reference equivalent ZCBYTM**

  Similar to approach one, this approach defines a reference equivalent ZCBYTM rate denoted as $YTM_{i,t}^{(RZCB),2}$. However, instead of fixed discounting factors, it calculates them based on tenors, using the corresponding U.S. Treasury par curve as follows:

$$YTM_{i,t}^{(RZCB),2} = \left[\frac{1}{\widetilde{FV_i}} \left(\sum_{n=1}^{\hat{N}} \frac{C_i \mathbb{I}(\tau_{i,n})}{(1 + (\frac{(r_t^{(Tr)}(\tau_{i,n})}{m_i}))^n} + \frac{FV_i}{(1 + (\frac{r_t^{(Tr)}(\tau_{i,N})}{m_i}))^N} \right) \right]^{-\frac{1}{N}} - 1, \quad (11)$$

  Where $r_t^{(Tr)}(\tau_n)$ and $r_t^{(Tr)}(\tau_N)$ represent yield rates extracted from Treasury par yield curves corresponding to their respective terms τ_n and τ_N at time t.

- **Spread Calculation**

  Similar to the previous approach, the non_parametric $S_{i,t}^2$ can be defined as follows:

$$S_{i,t}^2 := YTM_{i,t}^{(GZCB),2} - YTM_{i,t}^{(RZCB),2}. \quad (12)$$

Accordingly, the yield curve approach involves a collective number of points across the term structure of the green and reference curve, comparing a bootstrapped green bond curve versus a bootstrapped risk-free yield curve (e.g. par U.S. Treasury curve) on the same day when calculating the equivalent green and reference YTM. We compute the spread of the green bond i on day t and repeat this process for all green bonds available on this day.

2.2. Identify attributes of the green bond spreads via ARL

The study of associations between attributes of green bonds and their spread behaviors over time can be framed as an exercise in ARL, see Agrawal et al. (1993). ARL is a data mining technique that aims to uncover interesting relationships, patterns, or associations among items in large datasets. It is widely used in market basket analysis, customer segmentation, and recommendation systems. In traditional applications of ARL it is used to identify frequent itemsets, i.e. groups of items that co-occur frequently in transactions—and derives rules that describe their co-occurrence in terms of support, confidence, and lift. Support measures the frequency of an itemset, confidence evaluates the reliability of a rule, and lift quantifies the strength of the association beyond random chance.

In this work, we formulate an ARL solution in a time series context and seek associations of structuring attributes, including tax status, coupon rates, maturity, and credit rating, within a large collection of green bonds and their dynamic spread analysis over sliding windows of time, after their initial issuance. Traditionally, the learning of Association Rules (AR) in an ARL framework has to use an algorithmic search method. The Apriori algorithm is one of the most popular and foundational methods for ARL. It uses a bottom-up, breadth-first search approach to generate frequent itemsets, exploiting the property that any subset of a frequent itemset must also be frequent. Apriori operates in two phases: first, it identifies all frequent itemsets based on a minimum support threshold, and second, it generates association rules from these itemsets using a minimum confidence threshold.[6] A detailed explanation of the technical methodological aspects of the ARL framework and the Apriori algorithm are presented for completeness in the supplementary online Appendix A.[7]

2.2.1. Experimental Design

These association rules provide general rules that can inform issuers and help investors decide on green bond instruments for inclusion in green bond investment strategies. A screening process of practical relevance would be to identify structuring attributes associated with positive and negative green bond spreads. Positive spreads, where green bonds offer higher yields than a comparable benchmark, can arise due to factors such as market unfamiliarity, low liquidity concerns, and high credit risk in certain projects (Karpf and Mandel, 2018). In contrast, negative spreads can reflect high demand for sustainable investments, tax incentives, regulatory benefits, or strong creditworthiness and scarcity of issuance (Flammer, 2021; Fatica et al., 2021). Issuers may also offer lower yields to enhance their reputation

[6] While, the algorithm is efficient for smaller datasets, its performance can degrade with larger datasets due to the exponential growth in the number of candidate itemsets. Optimizations and alternative algorithms, such as FP-Growth, have been developed to address these challenges.

[7] A Bayesian network based approach to ARL implementing a probabilistic framework and extending the classical non-probabilistic ARL framework can also be used. This approach would reinterpret the confidence, support and lift as appropriate Bayesian posterior related quantities integrating prior beliefs or domain knowledge. See Appendix A.2. for the Bayesian ARL solutions that can be adopted in this work.

and attract a broader investor base. Furthermore, municipal green bonds are typically tax-exempt, making them particularly attractive to investors and allowing issuers to provide lower yields. Local investors may also accept reduced returns to support environmentally beneficial projects within their communities (U.S. Environmental Protection Agency, 2024). Note that "greenium", a central focus of many studies in the green bond market, specifically reflects the premium investors pay for the environmental benefits of green bonds (Zerbib, 2019). However, green bond spreads are broader measures capturing effects from a wide range of factors such as market conditions, tax incentives, as well as non-pecuniary incentives, e.g. environmental and reputational benefits.

Motivated by these insights and with the aim of offering a comprehensive screening assessment, our ARL approach would examine the structuring attributes associated with green bond spreads across five research objectives:

1. **Identifying Key Attributes for Positive and Negative Spreads**: Using Bayesian model selection, we identify the most significant rules that predict positive or negative spreads, highlighting primary bond attributes that influence spread behavior.
2. **Associations with Extreme Spread Magnitudes**: We assess whether spread sign predictors also correspond to extreme values, defining extreme spread ranges (upper and lower quantiles) and analyzing rules specific to these ranges.
3. **Temporal Consistency of Rules**: Using a sliding-window approach, we investigate the stability of key associations across different time periods, examining shifts in attribute importance over time.
4. **Impact of Specific Attributes on Spread Behavior**: By conditioning on core bond attributes (e.g., tax status, callability), we examine how conditioned rules vary, capturing how spread associations depend on specific bond features.
5. **Term Structure Attributes**: We study bond term structure attributes, focusing on associations between bond maturity, duration, and yield curve position with spread outcomes. This provides insights into how spread responses vary across the term structure, facilitating yield curve-based screening strategies.

This probabilistic approach to ARL offers a comprehensive assessment of green bond attributes in relation to yield spreads, with Bayesian model selection and sensitivity to priors providing robust and interpretable rule-based insights.

2.3. Data Description

For empirical analysis, we collect daily YTM data for the U.S. municipal green bonds from the Bloomberg Information Services terminal. Bonds are classified as "green municipal bonds" using Bloomberg's indicator function. Each bond, distinguished by a unique CUSIP number, serves as our observation unit. Furthermore, we gather 34 structuring attributes related to both the bonds and their issuers, as described in Appendix B, based on the CUSIP number. This CUSIP is used to match the yield datasets with the attributes datasets.

We use the yields of municipal green bonds issued in California between 2020 and 2023 in our data set.[8] California is the preferred state for this study for several reasons. It has a liquid green bond market in the U.S. compared to other states[9] and offers a wide variety of green bonds with diverse structuring properties. Additionally, the state has a stable taxation framework, a broad range of issuers, industries, and green projects (UOPs), and represents a significant issuance volume, accounting for more than 17% of the bonds in our dataset. Thus, California offers a good laboratory to study the structuring attributes of green municipal bonds and to inform screening practices. As we shall see in the following sections, the yield curve-based spreads computation requires bootstrapping of the yield curve of green bonds within certain partitions of similar characteristics, such as tax status and coupon. To allow a sufficient number of observations to be included in the bootstrapping exercise, we start our sample from 2020 and finish in 2023.

Several types of U.S. Treasury yield curves can be used to derive discount factors and serve as benchmarks for spread comparison.[10] In the context of a time series measured in monetary values, inflation is often a major driver and significant contributor to volatility (Cecchetti et al., 2007). In our analysis, where we specifically focus on nominal bond yields without adjusting for inflation, we choose par yields rather than the real par yields of U.S.

[8]To remove potential outliers in the yield variable, we employ a two-step iterative process based on Z-scores, which is detailed in Appendix C.

[9](California Green Bond Market Development Committee, 2023)

[10]Other reference risk-free U.S. rates, such as standard yield, inflation-adjusted yield, or real par yield, may also be utilized depending on the context.

Treasury bonds. The par yield of a security is related to the time until it matures, and its calculation uses the closing market bid prices of recently auctioned Treasury securities in the OTC market. The par yields are calculated from market prices, estimated quotes obtained by the Federal Reserve Bank of New York. Unlike the inflation-adjusted or real par yield curve, which incorporates inflation expectations, using par yields allows us to compare nominal yields without the additional adjustment directly. Both par and real par yield rates datasets are available from the U.S. Department of the Treasury.[11] A plot with the U.S. par yield data series is presented in Appendix D.

3. Calculation of the California green bond yield spreads

This section presents the details of the calculation of two novel measures of the green municipal bond spreads by using California green YTM; the tenor-specific spreads based on YTM, and the yield curve spreads based on the YTM term structure, as detailed in Section 2.1.

3.1. Calculation of the tenor-specific yield spreads

As explained in Section 2.1.1, the tenor-specific yield spreads are based on a single tenor point on both the green and reference yield curves, and are calculated by comparing green and risk-free zero-coupon bond yields at the same tenor point.

For each green bond i in California on day t, the observed $YTM_{i,t}$ is used to derive the green bond value $P_{i,t}$, and then the value of the equivalent zero-coupon green bond $P_{i,t}^{ZCB}$. From this value, we can obtain the equivalent zero-coupon green bond yield $YTM_{i,t}^{GZCB}$, (see Eq.(7)). To compute the equivalent zero-coupon reference rate $YTM_{i,t}^{RZCB}$ that matches the tenor $\tau_{i,N}$ year(s) of the green bond, (see Eq.(8)), we extract the corresponding rates $r_t^{(Tr)}(\tau_{i,N})$ from the U.S. Treasury curve on day t. To achieve this, we employ daily cubic Basis Spline (B-Spline) regression interpolation of the U.S. Treasury par yield rates in a bootstrapping procedure over a term structure range up to thirty years.[12] Finally, the

[11] U.S. Treasury Interest Rate Statistics

[12] Appendix E discusses the benefits of B-spline curves and presents demonstrative examples of the fit of the B-spline curves in the U.S. Treasury curve. A third-degree curve is selected for regression estimation (B3-spline) to enhance the accuracy of interpolation rate, thus three knot points are derived from the interquartile range and median.

difference of these two zero-coupon yields computes daily tenor-specific yield spreads, denoted as $S^1_{i,t}$, according to Eq. (9). Figure 1 depicts the median of the daily $S^1_{i,t}$, denoted as S_1, in California between 2020 – 2023.

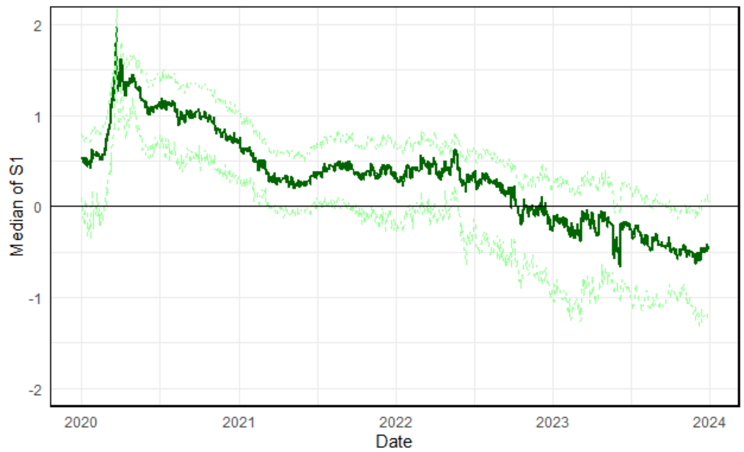


Figure 1: **Tenor-specific green bond yield spreads based on YTM**
This figure displays the daily median of the California tenor-specific green bond yield spreads, denoted as S_1, between 2020 – 2023. The green dashed lines represent the 25th and 75th percentiles of S_1.

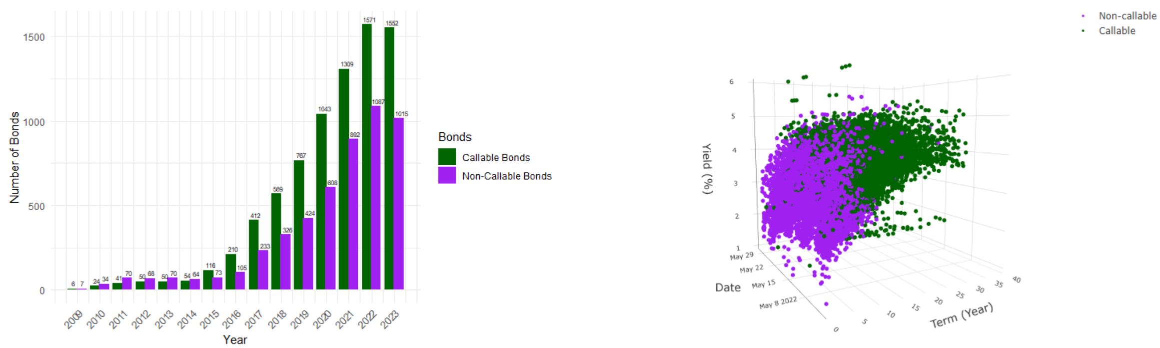
3.2. Calculation of the yield curve spreads based on the term structure of YTM

The yield curve spreads are based on a collective number of points along the term structure of the green and reference yield curves. These spreads are calculated by selecting appropriate discounting factors for the green bond cash flows from bootstrapped green bond curves and corresponding bootstrapped par U.S. Treasury curves, respectively. To construct comparable bootstrapped green bond curves, it is essential to group green bonds with similar structural characteristics. Accordingly, in the first step, we group the California green bonds, in the second step, we construct the bootstrapped curves, and in the last step, we compute the discounting spot rates, see Section 2.1.2 for details.

3.2.1. Step 1: Group the green bonds YTM

To improve the precision and reliability of discounting factors derived from observed yields in various terms, it is critical to systematically address variations in green bond prices and to create partitions of bonds or grouping bonds with similar structural features. A crucial aspect of this partitioning process is also to ensure that these bond groups include sufficient observations to reliably perform the yield curve bootstrapping for each green bond partition daily during the sample period. As detailed next, callability, coupon rate, and tax status are the most discriminatory structuring attributes of green bonds that exhibit clear patterns (clusters) in California green bond YTM.[13]

Callability: A call provision gives the issuer the right to redeem or “call” the bonds before their maturity date. This means that the issuer can buy back the bonds from the bondholders before they reach their scheduled maturity. The yield spread between callable and non-callable bonds of similar risk may vary. Callable bonds often offer a higher yield than non-callable bonds to compensate investors for the additional risk associated with potential early redemption (Chen et al., 2010).[14] Fig.2 (a) displays the number of callable and non-callable bonds in California between 2009-2023. The number of callable bonds exceeds the number of non-callable bonds and a steady growth in both callable and non-callable green bonds is evident.



(a) The count of callable and non-callable bonds between 2009-2023.

(b) Bond yield of callable and non-callable bonds in May 2022

Figure 2: **Callable and non-callable green bond issuance and yield variation**.
Panel (a) displays the count of municipal callabe and non-callable green bonds in California between 2009-2023. Panel (b) shows the callable (in green) and the non-callable (in purple) green bond yield in May 2022.

[13] Appendix F presents color-coded 3D plots of California green bonds’ YTM, based on various attributes. Analysis of these plots reveals distinct patterns in the YTM of green bonds for callability, coupon rate, and tax status, whereas distinct patterns are not observed for other attributes such as issuer industry, credit rating, market issue, and UOP.

[14] Callable bonds give the issuer the right to redeem the bonds before maturity, particularly when interest rates decline. If rates have fallen since the bond’s issuance, the issuer may choose to call the bond and issue new bonds at a lower interest rate, resulting in early redemption and impacting the investor’s yield. Callable bonds also introduce reinvestment risk for investors. Investors must reinvest the proceeds at the prevailing market interest rates if a callable bond is called. If rates have decreased, this reinvestment may occur at lower yields, reducing the overall return. Moreover, price volatility is a characteristic of callable bonds, which can be more pronounced than non-callable bonds, especially during interest rate volatility. A decline in interest rates increases the likelihood of the bond being called, potentially leading to capital losses for investors.

As an illustrative example, Fig.2 (b) shows callable (in green) and non-callable (in purple) green bond yields across the term structure in May 2022. As illustrated in this plot, callable bonds typically exhibit extended maturities and comparatively higher yields, which is a common feature of the spreads in our sample period, see Appendix G. Callable bonds often feature longer maturities because of the flexibility they provide to issuers. The callable feature allows issuers to redeem the bonds before their scheduled maturity, presenting advantages such as interest rate management and flexibility in adjusting debt portfolios. Issuers may issue callable bonds with longer maturities to take advantage of favorable changes in interest rates, and this flexibility can attract investors seeking longer-term commitments.

Coupon rates: The coupon rate is a key determinant of a bond's yield, impacting both its fixed income component and its attractiveness relative to prevailing interest rates. Higher coupon rates generally lead to higher yields, making a bond more appealing to investors in certain market conditions.[15]

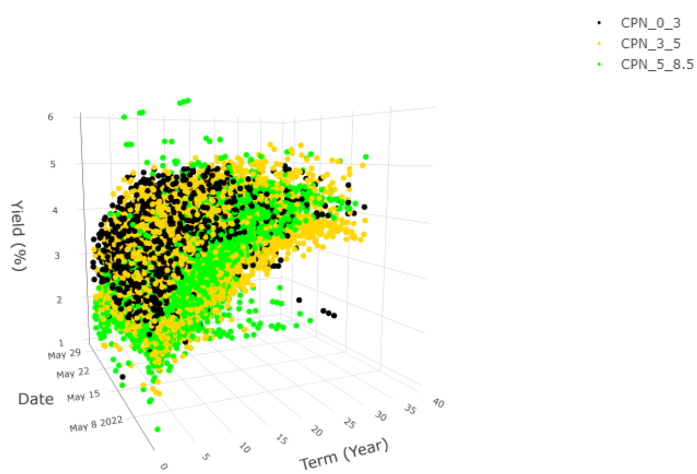
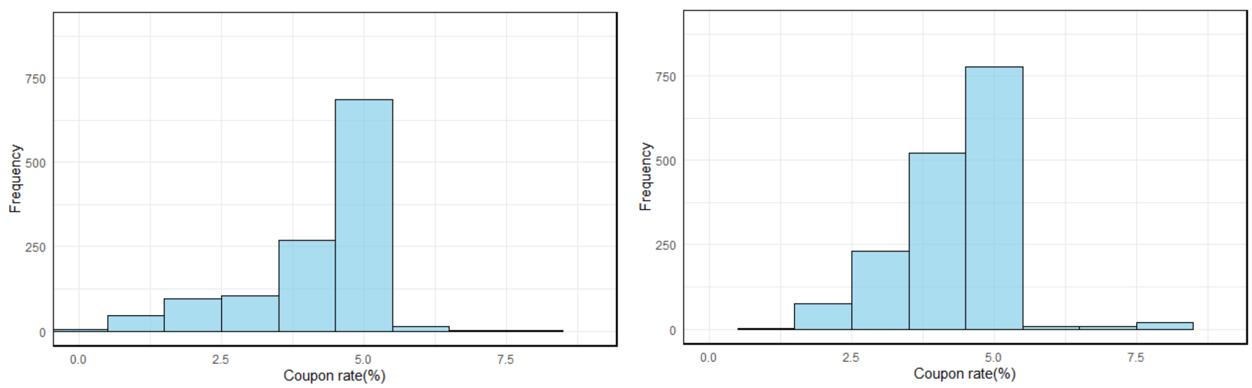


Figure 3: **Green bond yield in May 2022 color-coded by coupon.**
This figure depicts green bond yields in California in May 2022 color-coded by coupon; 0-3% in black, 3-5% in yellow and 5-8.5% in green.

[15]The coupon rate represents the fixed annual interest payment as a percentage of the bond's face value. This rate determines the fixed income component of the bond, contributing to a higher yield. Generally, bonds with higher coupon rates have higher YTMs, assuming the bond is trading at par. The coupon rate affects a bond's attractiveness to investors in a changing interest rate environment. If prevailing interest rates are lower than the bond's coupon rate, the bond becomes more attractive, potentially leading to increased demand and a higher price. Bonds with higher coupon rates are generally less sensitive to interest rate changes, providing a cushion against potential price declines.

We use Fig. 3 as an illustration for the coupon rates of green bond yields in California in May 2022. Clusters of coupon rates are evident for coupons rates between 0-3%, 3-5% and 5-8.5%. For a more comprehensive assessment of the characteristics of these clusters, we inspect the distribution of coupon rates for callable and non-callable bonds. Fig. 4(a) and (b) shows the distribution of coupon rates for callable and non-callable bonds in California, respectively and Table 1 provides a statistical overview of the coupon rates for callable and non-callable green bonds in our sample.



(a) Non-callable bonds coupon histogram.

(b) Callable bonds coupon histogram.

Figure 4: **Distribution of coupon rates for callable and non-callable bonds.**
This figure depicts the distribution of callable and non-callable green bond yields in California from 2020–2023.

Table 1: Statistical summary of coupon rates of green bonds in California

Type	No. of Bonds	Descriptive Summary of Coupon						
		Min.	1st Qu.	Median	Mean	3rd Qu.	Max.	St.dev.
Non-Callable	1226	0.20	3.32	4.00	4.08	5.00	7.69	1.21
Callable	1645	1.00	3.72	4.00	4.23	5.00	8.50	1.00

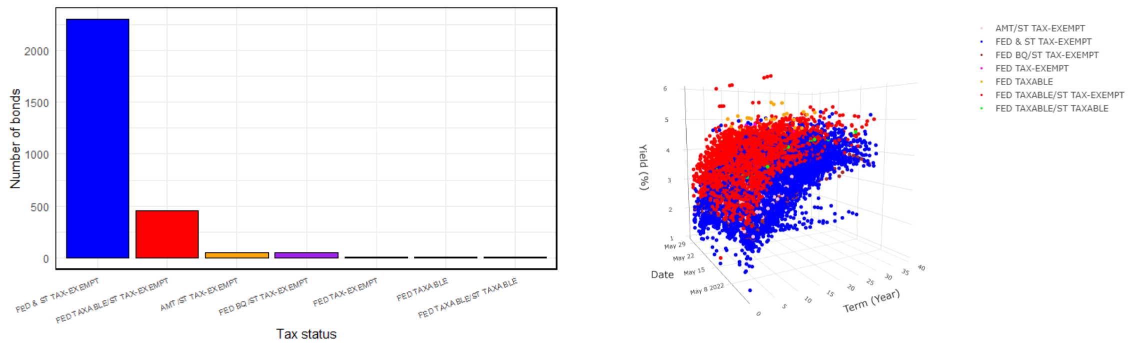
To ensure balanced sample sizes across partitions, it is important to find an optimal trade-off between the number of bonds and the coupon rate intervals. An efficient approach involves considering the quartiles of the coupon intervals for both callable and non-callable bonds. We accordingly segment the coupon range into three distinct partitions: minimum to the 1st quartile, 1st quartile to the 3rd quartile, and 3rd quartile to the maximum for each bond partition. To ensure well-defined and more precise intervals with a relatively similar range between callable and non-callable bonds, we round down the 1st quartiles of non-callable and callable bonds to 3.0% and 3.5%, respectively, and the 3rd quartiles of non-callable and callable bonds to 7.0% and 8.5%, respectively. Table 2 presents the statistical summary of the resultant partitions in our sample. As shown in the table, each partition includes a sufficient number of bonds to be used in the bootstrapping application and display suitable statistical properties.

Table 2: Statistical summary of non-callable and callable bonds for partitions of coupon rates

	Non-Callable								Callable							
Year	Coupon Rates (%)	No. of Bonds	Min	Max	Mean	Median	3rd Qu.	St.dev.	Coupon Rates (%)	No. of Bonds	Min	Max Max	Mean	Median	3rd Qu.	St.dev.
2020	[0.2-3.0)	86	0.59	2.94	2.33	2.44	2.44	0.44	[1.0-3.5)	205	1.70	3.50	3.02	3.00	3.00	0.28
	[3.0-5.0)	159	2.99	4.93	3.58	3.63	3.63	0.46	[3.5-5.0)	279	3.50	4.88	3.99	4.00	4.00	0.19
	[5.0-7.69]	363	5.00	7.69	5.11	5.00	5.00	0.38	[5.0-8.5]	558	5.00	8.50	5.26	5.00	5.00	0.82
2021	[0.2-3.0)	159	0.24	2.98	1.98	2.12	2.12	0.68	[1.0-3.5)	292	1.00	3.50	2.91	3.00	3.00	0.37
	[3.0-5.0)	294	2.99	4.86	3.75	4.00	4.00	0.41	[3.5-5.0)	442	3.50	4.84	3.99	4.00	4.00	0.15
	[5.0-7.69]	439	5.00	7.69	5.09	5.00	5.00	0.36	[5.0-8.5]	574	5.00	8.50	5.22	5.00	5.00	0.76
2022	[0.2-3.0)	160	0.20	2.98	1.85	1.98	1.98	0.68	[1.0-3.5)	303	1.00	3.50	2.82	3.00	3.00	0.42
	[3.0-5.0)	309	2.99	4.93	3.80	4.00	4.00	0.38	[3.5-5.0)	523	3.50	4.88	4.00	4.00	4.00	0.14
	[5.0-7.69]	618	5.00	7.69	5.05	5.00	5.00	0.28	[5.0-8.5]	744	5.00	8.50	5.18	5.00	5.00	0.68
2023	[0.2-3.0)	142	0.32	2.94	1.85	1.98	1.98	0.68	[1.0-3.5)	297	1.00	3.50	2.83	3.00	3.00	0.42
	[3.0-5.0)	296	2.99	4.93	3.81	4.00	4.00	0.38	[3.5-5.0)	518	3.50	4.88	4.00	4.00	4.00	0.14
	[5.0-7.69]	577	5.00	7.69	5.05	5.00	5.00	0.26	[5.0-8.5]	736	5.00	8.50	5.15	5.00	5.00	0.60

Tax status: The tax status of bonds can influence the yields of bonds. Since investors receive tax benefits, tax-exempted bonds yields could be lower than taxable ones with similar risk profiles.[16] Fig. 5(a) shows the tax status frequency in California and Fig. 5(b) shows the green bonds yields for different tax statuses in May 2022. The tax status of green bonds in California is concentrated in two categories: the *Federal and State Tax Exempt* (represented by blue spots) and *Federal Taxable and State Tax Exempt* status (represented by red spots), see Appendix B for the corresponding definitions of the tax statuses. As Fig. 5 reveals, most of the green bonds in California are *Federal and State Tax Exempt* and typically, the *Federal and State Tax Exempt* bonds have comparatively lower yields relative to the *Federal Taxable and State Tax Exempt* bonds.

[16] Taxes affect municipal bond yields because the interest income from these bonds is typically exempt from federal income tax, and sometimes state and local taxes as well. This tax advantage makes municipal bonds more attractive to investors in higher tax brackets, allowing issuers to offer lower yields compared to taxable bonds. In contrast, bonds without such tax exemptions need to offer higher yields to compensate investors for the tax burden. Therefore, the tax status of a bond directly influences its yield (Cestau et al., 2019; Perlovsky and DeMarco, 2018).

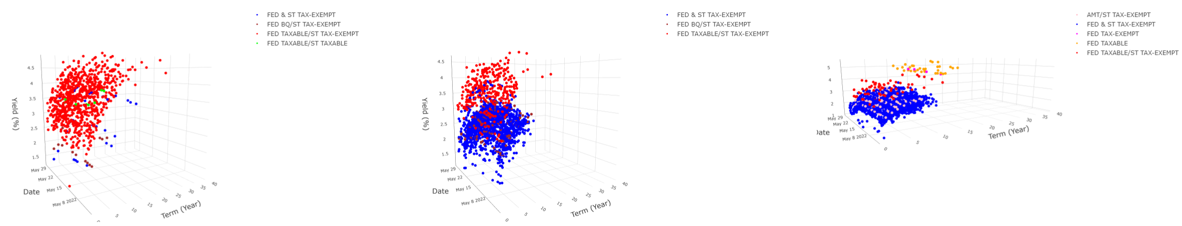


(a) Green bonds tax status in California.

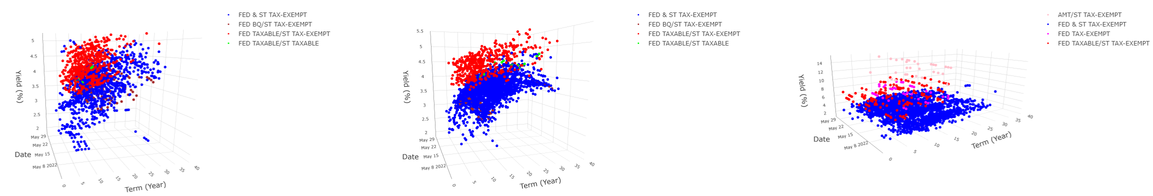
(b) Bond yields in May 2022

Figure 5: **Green bonds tax statuses and yield in May 2022 color-coded by tax status.** This figure depicts the number of green bond according to tax status and green bond yields in California color-coded by tax status. Panel (a) depicts the number of bonds within each tax province in our data set and panel (b) shows the bond yield in May 2022 color-coded by tax status – blue for *Federal and State Tax Exempt*, red for *Federal Taxable and State Tax Exempt* and other colors for the remaining statuses.

After we partition the sample of green bonds according to the coupon rate and callability, and examine the concentration of the tax status of the bonds within each of these partitions. Figure 6 provides a visual representation of the concentration of tax statuses across the coupon rate and callability partitions, where interesting clustering properties emerge in a representative sample in May 2022. Note that California municipal green bonds exhibit similar characteristics during the sample period (2020-2023) as depicted in Appendix G.



(a) Non-callable bond yield for coupon [0.2-3.0%) (b) Non-callable bond yield for coupon [3.0-5.0%) (c) Non-callable bond yield for coupon [5.0-7.0%]



(d) Callable bond yield for coupon [1.0-3.5%) (e) Callable bond yield for coupon [3.5-5.0%) (f) Callable bond yield for coupon [5.0-8.5%)

Figure 6: **Green bond yield in May 2022 color-coded by tax status for partitions of the coupon rates.** This figure depicts non-callable (top panels) and callable (bottom panels) green bond yields in California color-coded with tax status for partitions of coupon rates in May 2022. The *Federal Taxable and State Tax Exempt* (FTSE) and *Federal and State Tax Exempt* (TE) are represented in red and blue spots, accordingly.

Accordingly, we make the partitions of the green bonds in California to ensure representative sufficiently balanced sub-samples in each partition based on their callability, coupon rates, and tax status. We use the abbreviation FTSE for *Federal Taxable and State Tax Exempt* bonds,[17] and TE for all tax-exempt bonds,[18] with *Federal and State Tax Exempt* bonds comprising the majority of this category.

- Group 1 (G1): This partition includes non-callable bonds with coupon rates ranging from 0.20 - 3%, see Fig. 6(a). This partition prominently features bonds categorized as FTSE (represented by red spots). Consequently, no further separation is considered necessary for this specific partition.

- Groups 2 and 3 (G2 and G3): This partition covers non-callable green bond yields with

[17]To maintain a homogeneous representation of tax implications, we exclude other taxable bonds, including *FED TAXABLE* and *FED TAXABLE/ST TAXABLE*, which have the lowest counts of 6 and 5 green bonds, respectively (see Fig. 5(a)) ensuring that our taxable bonds represent the *Federal Taxable and State Tax Exempt* status.

[18]Other tax-exempt bonds include *AMT/ST TAX-EXEMPT*, *FED BQ/ST TAX-EXEMPT* and *FED TAX-EXEMPT*.

coupon rates from 3 - 5%, see Fig. 6(b). These bonds have clear clustering on two tax statuses, FTSE and TE. Thus, we distinguish between these two groups of bonds and label the FTSE and TE partitions as Groups 2 and 3, respectively.

- Group 4 (G4): This partition covers non-callable bond yields with coupon rates from 5 - 7.69%, see 6(c). There is a predominant concentration of bonds with the TE and the FTSE tax status. The challenge is that the number of FT bonds is insufficient for proper segmentation. Thus, no additional partitioning was considered in this coupon partition of non-callable bonds, and we anticipate relatively noisier patterns from this group of bonds.

- Groups 5 and 6 (G5 and G6): This partition considers callable green bonds with coupon rates ranging from 1 - 3.5%, see Fig. 6(d). For these bonds, there is a clear distinction between FTSE and TE bonds labelled as Groups 5 and 6, respectively.

- Groups 7 and 8 (G7 and G8): This partition includes callable green bonds with coupon rates ranging from 3.5 - 5%, see Fig. 6(e). We further separate the FTSE and TE bonds within this partition and obtain the groups Groups 7 and 8, respectively.

- Groups 9 (G9): This partition considers callable green bonds with coupon rates ranging from 5 - 8.50%, see Fig. 6(f). Most of these green bonds belong to the TE tax status. There is a group with bonds from other tax status, predominantly FTSE tax status, however, the quantity of these bonds is not sufficient for a robust segmentation. We keep this as one group labelled as Group 9 and we anticipate noisier bootstrap curves on some days from this group.

Table 3 summarizes the nine groups of green bonds and their descriptive summary. These groups seem to reflect their structural characteristics well, and we use them next in the bootstrapping application to construct green bond yield curves from which we obtain suitable discount rates for the green bond cash flows.

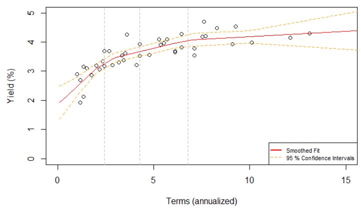
Table 3: Specifications of the green bonds groups used in the bootstrapping application

Group	Callability	Coupon range	Tax status	No of bonds	Yield Descriptive Summary		
					Mean	Median	St.dev.
G1	Non-Callable	[0.20-3.00)	All	182	2.89	2.57	1.59
G2	Non-Callable	[3.00-5.00)	FTSE	289	2.63	2.10	1.49
G3	Non-Callable	[3.00-5.00)	TE	56	1.88	2.03	1.05
G4	Non-Callable	[5.00-7.69]	All	692	1.78	1.93	1.21
G5	Callable	[1.00-3.50)	FTSE	216	3.52	3.05	1.22
G6	Callable	[1.00-3.50)	TE	91	2.88	2.67	0.88
G7	Callable	[3.50-5.00)	FTSE	448	3.81	3.62	0.97
G8	Callable	[3.50-5.00)	TE	80	3.07	3.10	0.82
G9	Callable	[5.00-8.50]	All	806	3.24	3.16	1.33

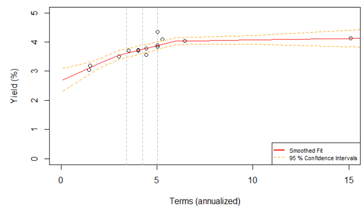
3.2.2. Step 2: Daily yield curve construction via bootstrapping

In the yield curve spread calculation approach, we estimate bootstrap curves on a daily basis within bond partitions, as discussed in the previous section. This enables us to derive $r_t^{(G)}(\tau_{i,n})$, where $n \in \{1, \ldots, N\}$, which is then utilized for discounting the cash flows associated with green bonds, as specified in Eq. (10). Due to the partitioning of data, we have yield data specific to limited ranges of terms across the term structure in each partition. Additionally, there may be instances where certain partitions have a limited number of data points on certain days. In light of these considerations, we employ a B1-spline regression estimation in the construction of bootstrap curves with three-knot points from the interquartile range and median. This choice helps mitigate the impact of noise or overfitting in the curves.

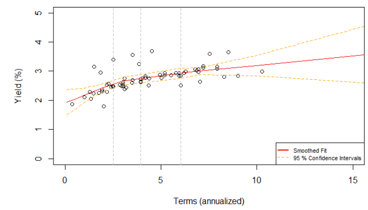
Fig. 7 illustrates the B-spline bootstrap curves fitted to the partitions outlined in the preceding section. Although the overall accuracy of the fitted bootstrap curves is satisfactory, we observe a somewhat noisier curve in both G4 and G9, as anticipated.



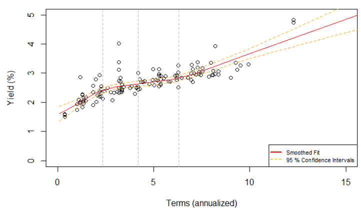
(a) B1-spline bootstrap curve fitted in G1



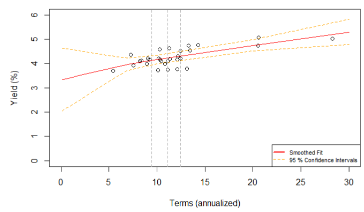
(b) B1-spline bootstrap curve fitted in G2



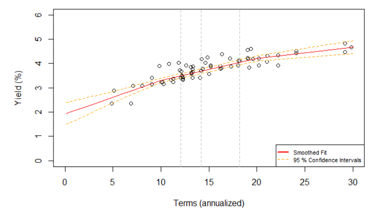
(c) B1-spline bootstrap curve fitted in G3



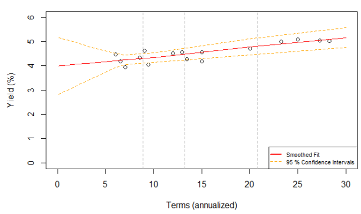
(d) B1-spline bootstrap curve fitted in G4



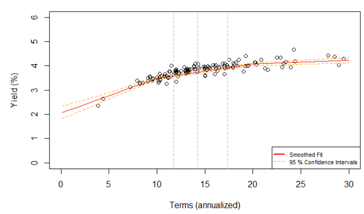
(e) B1-spline bootstrap curve fitted in G5



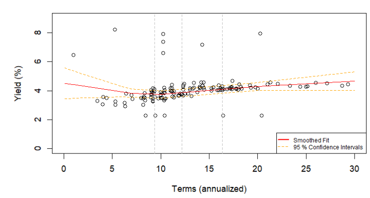
(f) B1-spline bootstrap curve fitted in G6



(g) B1-spline bootstrap curve fitted in G7



(h) B1-spline bootstrap curve fitted in G8



(i) B1-spline bootstrap curve fitted in G9

Figure 7: **B1-spline bootstrap curve fitted for bonds groups on 2022-05-23.**
The red line represents the fitted B1-Spline bootstrapped curve, while the dotted orange curve depicts the 95% confidence intervals for the predicted rates. The grey vertical lines represent the control points or knots for each group.

3.2.3. *Step 3: Determination of spot rates for discounting and computation of yield curve spreads*

As explained in Section 2.1.2, the yield curve approach requires points across the term structure of both the green and reference yield curves, using the bootstrapped California green bond curve and a bootstrapped U.S. Treasury yield curve. Thus, the equivalent green and reference YTM are calculated by a daily curve-to-curve comparison between green and risk-free zero-coupon bond yields.

More specifically, for each green bond i in California on day t, the corresponding $YTM_{i,t}$ from the bootstrapped green bond curve is used to discount each cash flow of the bond $P_{i,t}$ to obtain the value of the equivalent zero-coupon green bond $P_{i,t}^{ZCB}$. From this value, we can obtain the equivalent zero-coupon green bond yield $YTM_{i,t}^{GZCB}$ from Eq. (10)). Next, we extract the corresponding rates $r_t^{(Tr)}(\tau_{i,N})$ from the U.S. Treasury curve on day t, to compute the equivalent zero-coupon reference rate $YTM_{i,t}^{RZCB}$ that corresponds to the tenors of cashflows of the green bond i, according to Eq. (11). Recall that the daily cubic Basis Spline (B3-Spline) regression interpolation of the U.S. Treasury par yield rates is used to construct the reference yield curve from which we select the appropriate discounting reference rates, see Appendix E. Lastly, according to Eq. (12), the difference of these two zero-coupon yields computes daily yield curve spreads, namely $S^2_{i,t}$.

Figure 8 depicts the daily median of yield curve spread $S^2_{i,t}$, denoted as S_2, in California between 2020 – 2023. For comparison, we also include the daily median of the tenor-based spreads, namely S_1, during the sample period. There is an overall downward trend in both green bond yield spreads, and they are on average positive and disparate, but they reach negative territories and converge after 2022. In particular, there are three distinct periods separated by the dates 2021-05-13 and 2022-09-06. In the first period, the trend is very steep; in the second period, the spreads are rather flat; and in the last period, the spreads become negative and downward trending again.

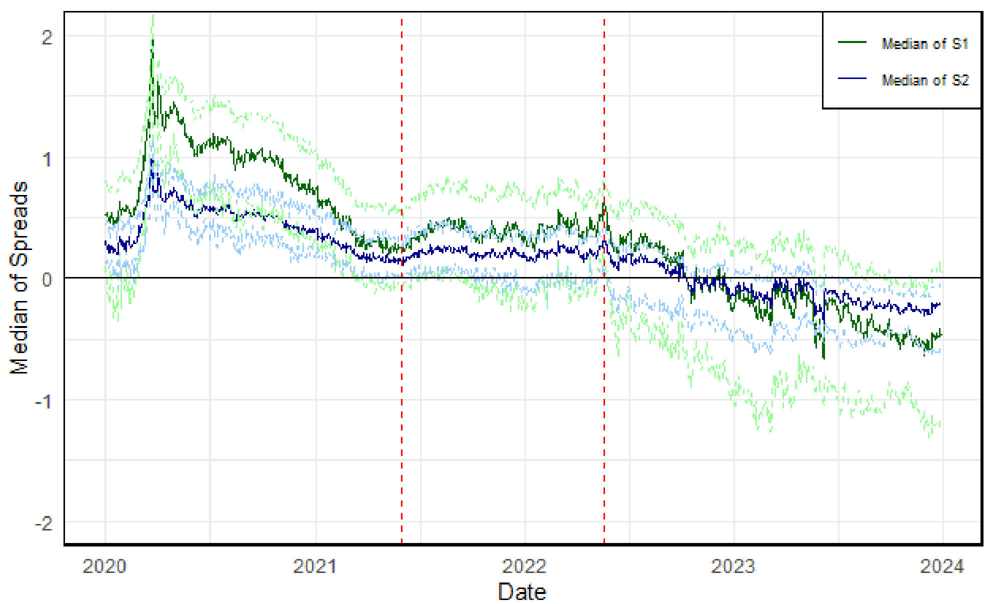
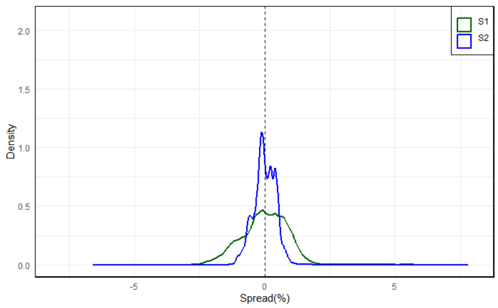


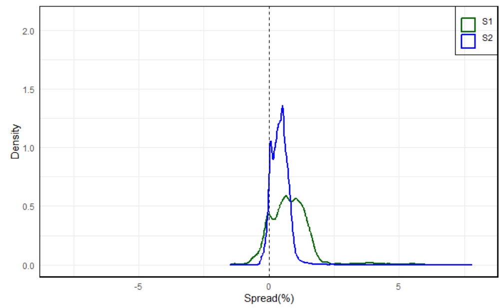
Figure 8: **Green bond spreads based on YTM and their term structure.**
This figure displays the daily median of the California tenor-specific green bond yield spreads based on YTM, S_1, (in green) and the yield curve spreads based on their YTM term structure, S_2, (in blue) between 2020 – 2023. The dashed lines represent the 25th and 75th percentiles. The two vertical dashed lines mark the dates 2021-05-13 and 2022-09-06.

3.3. *Statistical properties of green bonds spreads*

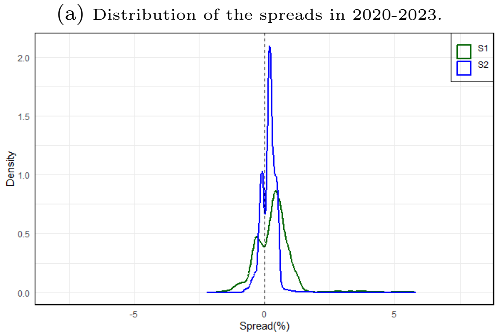
The statistical properties of the two novel spreads reveal their distinctive characteristic. Figure 9 compares the distributions of the two spreads and Table 4 provides a statistical summary of two spreads between 2020 and 2023 as well as in the three periods separated by 2021-05-13 and 2022-09-06, in which the spreads display different trends and behavior.



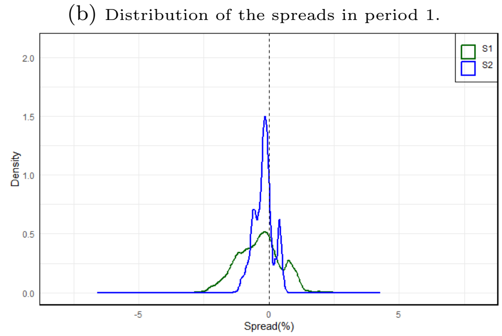
(a) Distribution of the spreads in 2020-2023.



(b) Distribution of the spreads in period 1.



(c) Distribution of the spreads in period 2.



(d) Distribution of the spreads in period 3.

Figure 9: **Distribution of the green bond spreads.**
This figure illustrates the distribution patterns of the two green bond spreads S_1 and S_2 for the entire sample interval (2020-2023) and for three periods separated by the dates 2021-05-13 and 2022-09-06. The green and blue curves represent the distributions of S_1 and S_2, respectively.

Table 4: Statistical Summary for Spreads

Year	Spread	Descriptive Statistics						
		Min	1st Qu.	Median	Mean	3rd Qu.	Max	St.dev.
Total	S_1	-6.58	-0.56	0.04	0.01	0.79	7.80	0.92
	S_2	-2.68	-0.25	-0.01	0.00	0.31	3.51	0.42
Period 1	S_1	-1.50	0.28	0.75	0.80	1.21	7.80	0.82
	S_2	-0.53	0.19	0.41	0.42	0.62	3.51	0.31
Period 2	S_1	-2.20	-0.01	0.36	0.33	0.67	5.81	0.70
	S_2	-0.88	-0.02	0.19	0.17	0.34	3.07	0.27
Period 3	S_1	-6.58	-0.97	-0.35	-0.37	0.17	4.28	0.83
	S_2	-2.68	-0.46	-0.19	0.06	-0.01	0.92	0.37

In the whole sample, the mean of both spreads is close to zero, and the spread S_1 shows a higher median and standard deviation compared to the spread S_2. Given the substantial variations of the spread over these four years, the statistical properties of the spreads over the three sub-periods tend to be more informative. More specifically, the spread S_1 shows a higher mean, median, and standard deviation compared to the spread S_2 in the first and second periods. However, in the third period, there is overlap in the spreads and S_1 displays a lower median compared to the spread S_2. These observations are also supported by the corresponding descriptive statistics of the three periods summarized in Table 4.[19] Furthermore, the medians of the spreads are positive in the first two periods, but both reach negative territories in the third period.

These observations confirm the distinct nature of each of these two spreads and affirm the merits of investigating the potential driving attributes of the two spreads. Despite the fact that the focus of this study is the identification of spreads' attributes from a screening perspective for investors or issuers, we briefly conjecture of potential macroeconomic drivers that may explain such trends. The noticeable downward trend in both spreads over time may be driven by an increase in the demand for green bonds due to a shift in ethically mo-

[19]In Period 1, the spread medians for S_1 and S_2 are 0.75 and 0.41, respectively, while in Period 2, the spread medians reduce to 0.36 and 0.19, respectively. In Period 3, both S_1 and S_2 show a significant decrease in the median, falling to -0.35 and -0.19, respectively. Furthermore, S_1 consistently shows a wider range and higher variability (standard deviation) compared to S_2.

tivated investors' preferences in meeting sustainability targets.[20] In addition, during 2021, the substantial gap between the two spreads emerges alongside a declining trend in interest rates and the slope rate of interest rates (or convexity). With an increase in convexity in 2022, the two spreads begin to converge. Eventually, as the convexity reaches zero and turns positive, the spreads approach zero and then turn negative in 2023. Thus, amongst other macro-economic factors, these fluctuations and trends may reflect responses to "contractionary" monetary policy during this period. The plots depicting the trends in interest rates, the U.S. Treasury par yield curve convexity, and the slope are presented in Appendix D. The complete investigation of the macroeconomic drivers of spread behavior is beyond the purpose of this study. These investigations consist of the topic of the authors' upcoming research.

4. Attributes associations of green bonds spreads

In this section, we use ARL to identify and analyze the attribute associations of the green bond yield spreads for screening applications. To address the research questions detailed in Section 2.2.1, we first identify the first-order attribute associations of the positive and negative green bond spreads. Next, we elaborate on the associated attributes of the extreme (positive and negative) spreads and further investigate the temporal consistency of their strongest attribute associations. To inform a more comprehensive screening practice, we finally examine the attribute associations within a specific type of green bonds by conditioning the rules on attributes of interest such as callability and tax status. Note that we perform the above-mentioned analysis for both spreads, namely the daily median of the tenor-based spreads S_1 and the daily median of the yield curve spreads S_2, to compare and contrast their corresponding attribute associations. Based on their distributional properties (skewness), see Fig. 9, the daily median of these spreads serves as a representative central measure for the analysis.

[20] This demand is driven by institutional investors like pension funds, which seek to hedge against long-term risks such as climate change while meeting regulatory and beneficiary demand for ESG-aligned investments. Similarly, insurance companies use green bonds to match liabilities, aligning their long-term liabilities with sustainable assets that mitigate climate-related risks. Recent studies highlight the emergence of a premium in the U.S. municipal bond market driven by growing investor preferences for sustainable investments (Karpf and Mandel, 2018).

4.1. Labelling process, parameters setting and model order selection

To apply ARL we perform the following preparation steps. First, we categorize the attributes (defined in Appendix B) according to their characteristics and assign appropriate labels through a systematic labeling process for categorical and numerical attributes, as detailed in Appendix H. We also denote by $S_1(+)$ and $S_2(+)$ the positive daily median of the two spreads and by $S_1(-)$ and $S_2(-)$ the corresponding negative daily spread medians. The next step involves determining suitable thresholds that generate possible rules for positive and negative spreads. These thresholds are based on the first confidence quantiles of all rules in our itemsets, allowing us to discover rules with the highest confidence level within the most frequent ones in the dataset, which we refer to as strong rules. The process of generating general rules and selecting parameter thresholds is detailed in Appendix I.[21] After implementing the corresponding thresholds for positive and negative spreads, we obtained subsets of rules for positive and negative spreads, spanning orders 2 to 5.[22]

Lastly, to determine the order[23] of the model through BMS, we assume a uniform distribution for prior probabilities and model parameters (see Appendix A.3. for the technical details). Using the conditional probability of the rules (confidence) within each order, we compute the posterior probabilities for each model order, see Table 5. Accordingly, for S_1, the posterior probability of models with positive spreads decreases as the model order increases, while the opposite trend is evident for negative spreads, while for S_2, the posterior probability increases in alignment with the order of the rules. Given the minimal difference between model orders, we examine all orders, with particular attention to those showing higher posterior probabilities.

[21]We set a min_supp of 0.1 for both positive and negative spreads of S_1 and S_2 and a min_conf thresholds of 0.65 and 0.60 for positive rules, and 0.45 and 0.4 for negative rules, for S_1 and S_2, respectively.

[22]We use version 1.7-7 of the arules package in R, which includes the Apriori, Eclat, and FP-Growth algorithms for mining association rules and frequent itemsets. More specifically, we used the Apriori algorithm in this research(Hahsler et al., 2023). Within the context of the *arules* package in R, "order 2" signifies rules with one item in the antecedent (lhs) and one item in the consequent (rhs).

[23]In association rule learning, "order" refers to the number of items (variables) involved in a rule. In the context of the arules package in R, "order 2" specifically indicates rules with one items in the antecedent (lhs) and one item in the consequent (rhs).

4.2. Attributes of positive and negative green bond spreads

We identify the attribute associations of positive and negative spreads by considering one itemset (order 2 rules) to generate association rules for positive and negative spreads.[24] Table 6 presents the most frequent rules (ranked by confidence) for positive and negative spreads S_1 and S_2 and the comparison of attribute support and confidence for the two spreads is depicted in Fig. 10.

Several findings emerge with respect to the attributes associated with positive spreads. The spreads S_1 and S_2 identify tax status (specifically, federally taxable[25] bonds) and pricing strategy (specifically, at-par) as the two highly associated attributes for positive spreads. Furthermore, maturity-related attributes and spread at issuance (S_OID) of both spreads are strongly associated (as reflected by the support) with positive spreads. However, rules related to maturity, callability (callable), and duration rank higher for yield curve spreads S_2, while coupon range (lower coupon) ranks as one of the highly associated attributes with positive tenor-specific yield spreads S_1 but not for spreads S_2.

Regarding attributes related to negative spreads, we find that S_OID, maturity (in lower categories), and callability (non-callable), are the most frequent attributes for both spreads. Similarly to positive spreads and based on the support measure, maturity, callability (non-callable), and duration hold stronger associations with yield curve spreads (S_2), while yield on issue date (Y_OID) ranks higher for yield spreads S_1.

In summary, tax status and pricing strategy are the most frequent attributes associated with positive spreads, while S_OID, maturity, and (non-)callability are the most common attributes with negative spreads. In addition, the low coupon yield is related only to the positive yield spread S_1, and the yield curve spreads (S_2) have additional attributes strongly associated with positive and negative spreads, including maturity and duration.

4.2.1. Statistical significance of ARL results

To verify the statistical significance of the ARL results (order 2), we perform a one-way ANOVA test on the frequently identified attributes. To define subsamples for the

[24] We set the right-hand side ($lhs => rhs$) of the rules as $S(+)$ and ($S(-)$), representing positive and negative spreads, respectively.

[25] FED TAXABLE/ST TAX-EXEMPT

ANOVA test, we categorize according to maturity (Maturity_OID), which is a common frequent attribute previously identified.[26] We then investigate whether the contributions of the levels of other strong attributes to the spread variation are statistically significant.[27] The hypothesis development, results of the ANOVA tests, and box plots for different attributes across all maturity categories are presented in Appendix J.

We find that the null hypothesis for all ANOVA tests for the top seven attributes can be rejected in favor of the alternative hypothesis (H1). More specifically, the contribution of tax status and at-par pricing type remains relatively stable across maturities. However, the contribution of the low coupon range to spread variation is more pronounced in short maturities and decreases as maturities increase. The S_OID and Y_OID play a greater role in spread variation in short maturities, whereas bonds with higher duration contribute more to spread variation in longer maturities, and vice versa. Furthermore, for longer-term bonds, the callability contributes to the spread variation. The issued amount only contributes to the variance in spreads at higher maturities, and the null hypothesis of the ANOVA test cannot be rejected for the first three maturity categories in S_1 and the first category in S_2.

4.2.2. Exploring higher-order rules using nested rules

This section delves into higher-order association rules. We use nested rules based on the identified strong association rules from previous orders to explore higher-order rules to the fullest extent possible. Thus, we keep the highly ranked rules from lower-order levels, allowing us to observe how different attribute states associate with the currently identified strong rules.[28] Fig. 11 depict the higher-order rules for positive and negative spreads of spreads S_1 and S_2, respectively.

Analysis of higher-order rules reveals several interesting results for positive green bond spreads. First, tax status consistently emerges as a dominant associated attribute in higher-

[26]We categorized green bonds based on their maturity since this characteristic affects the Investor's decision to manage convexity risk in fixed income investments. Also, maturity impacts the liquidity, with longer-term bonds experiencing higher demand due to reduced trading activity and investor preference for longer-term investments.

[27]Since we categorized green bonds according to Maturity_OID, we didn't include the other maturity-related attribute, R_Ys_to_Maturity, in the ANOVA test.

[28]Since we use the strongest rules with lower order as the nested rules, higher-order rules consisting of nested rules may not exist in some cases.

order rules for both spreads (but to a lower extent for spread S_2). Thus, federally taxable bonds with attributes such as at-par pricing, absence of a credit rating (BB_rating), self-reported green status, and revenue bonds are more likely to have a positive spread. However, callability and maturity became more critical in higher-order rules for yield curve spreads S_2. Second, in higher-order rules, the tax status, pricing strategy, and self-reported green status constitute strong rules for both types of spreads. As the order increases for positive spread, there is a noticeable decrease in the number of strong rules that aligns with the results of BMS.

Based on higher-order rules, negative spreads are highly associated with callability (non-callable bonds) and maturity (less than 8 years). However, for yield curve spreads S_2, duration plays a critical role in higher-order rules. In particular, there is an increasing trend in both support and confidence as we progress to higher-order rules.

Thus, the higher-order rules analysis confirms consistent results with the second-order analysis for both spreads. Positive spreads are related to tax status, pricing strategy, and self-reported green status, while negative spreads are related to callability (non-callable) and maturity (less than 8 years). In particular, for yield curve spreads S_2, callability and maturity are related to positive spreads, while duration is linked to negative spread.

4.3. Attributes contributing to extreme positive (negative) green bond spreads

This section examines attributes associated with extreme positive and negative green bond spreads. For negative spreads, we consider the lower quantile as *extreme negative* ($S(\text{extreme}(-))$), and for positive spreads, we denote the upper quantile as *extreme positive* ($S(\text{extreme}(+))$).[29] Fig. 12 shows the attribute associations for extreme positive and negative spreads, in parallel coordination and different orders.

We find that tax status (federal taxable) and callability (callable) play a strong role in rules with different orders for extreme positive spreads, a result that holds for both types

[29] For generating rules for the extreme spreads, we designated the right-hand side ($lhs => rhs$) of the rules as $S(\text{extreme}(+)$ or $S(\text{extreme}(-)$. Limited to 50% of observations for this analysis, we applied a min_supp of 0.01 and a min_conf similar to the previous step to identify rules associated with extreme positive (or extreme negative) spreads in the dataset. To enhance the extraction of meaningful and robust rules, and since we employ a relatively lower threshold for support, we introduce a new measure, which is the product of support and confidence ($supp\_conf$). This measure allows us to pinpoint rules with high support and confidence simultaneously.

of spreads. However, other key attributes for extreme positive yield spreads S_1 include credit rating (not-rated bonds), Y_OID (highest categories), S_OID (highest categories), and pricing type (at-par). For yield curve spreads S_2, callability plays a more critical role in strong rules (compared to the S_1 spread), and maturity emerges as an additional strong rule. Furthermore, higher-order rules become stronger and a more complicated structure of attributes emerges for yield curve spreads (S_2).

The attributes associated with extreme negative spreads include tax status (federal exempt) and callability (non-callable) which play a dominant role in rules with different orders for both spreads. In particular, tax status (federal exempt) plays a more important role in extreme negative rules than in extreme positive rules (which are federal taxable). Along with callability and tax status, maturity and duration became frequent attributes associated with extreme negative yield curve spreads S_2. In fact, extreme negative values of S_2 are associated with more complicated rules and higher strength.

To conclude, extreme positive and negative spreads are associated with tax status and callability, with callability being more frequent for S_2. However, extreme positive S_1 spreads also relate to credit rating (not-rated bonds), yield and S_OID (highest categories), and pricing type (at-par), while extreme negative (positive) S_2 spreads have more complicated structures typically associated with maturity and duration (maturity).

4.4. Temporal consistency of rules

We further investigate the consistency of the attribute associations over time. Fig. 13 provides comparative graphs to illustrate the confidence trends of associated attributes (for the rules of order 2) within each year in the sample.

It is evident that for positive yield spreads $S_1(+)$, tax status, pricing strategy, and coupon range are the most stable attributes, with tax status consistently at the maximum level throughout the period. Similarly, tax status and pricing strategy hold the same rank for positive yield curve spreads $S_2(+)$. However, tax status loses maximum confidence towards the end of the interval, and the absence of coupon range becomes noticeable among the most important attributes. Furthermore, the downward trend in confidence is stronger for other frequent attributes, such as maturity, callability, spread at issuance, and duration.

Negative spreads exhibit an upward trend in confidence for both spreads, with a decrease in the growth rate in the middle of the interval, followed by an increase towards the end of the interval. However, S_OID demonstrates a greater distance from other attributes, and the growth rate for pricing type confidence is relatively higher for yield curve spreads $S_2(+)$. Overall, the attribute associations tend to be consistent over time for positive spreads, but an upward trend in confidence is present in the attribute associations of negative spreads.

4.5. Assessment within bonds with specific attributes

In this section, we condition the *lhs* of the rules on specific attributes or on a particular state (or category) of an attribute. This allows us to examine the attribute associations of green bond spreads within a particular type/group of green bonds. As the analysis above demonstrate, callability and tax status of green bonds are critical structuring attributes, thus we next assess attribute associations of positive and negative green bonds of a certain callability and tax status. For more targeted reflections on the potential environmental impact of the spreads, we also examine attribute associations of positive and negative green bonds within certain issuer sectors and UOPs.

4.5.1. Callability-based attribute associations

Fig. 14 displays the most frequent callability-based attribute associations for positive and negative spreads. We find that callable bonds that are tax-exempt or issued at a premium are more likely to have a positive spread (for both spreads). In addition, longer maturity remains a stable attribute associated with positive spread within callable bonds, while pricing at par matters for callable negative yield curve spreads $S_2(-)$.

For non-callable bonds with a positive spread, the strongly associated attributes are the same across both spreads and include federal taxable bonds, bonds issued at par, and bonds with low coupon range. In terms of negative spreads of non-callable bonds, tax status, and pricing at premium matter for both spreads.

4.5.2. Tax-based attribute associations

The more frequent attributes for tax-based (federally taxable or tax-exempt) associations for the two spreads are presented in Fig. 15. Regarding attributes of federally taxable green bonds, we find that these green bonds, when issued at par, are strongly associated with positive spreads with other important attributes, including being self-reported as green, having no credit rating, and being issued as revenue bonds across both spreads. Furthermore, the most frequent attribute of federally taxable green bonds is a higher coupon rate, which is associated with negative yield curve spreads $S_2(-)$.[30]

The attributes of tax-exempt green bonds with positive spreads include callability, issued at a premium, self-reported green, long maturity, and a high coupon range. The importance of maturity-related attributes becomes more prominent for yield curve spreads S_2. Tax-exempt green bonds with negative spreads (for both spreads) exhibit strong associations with bonds issued at premium or with low maturities. Spread at issuance gains more importance for yield spreads S_1, while maturity-related attributes display a higher frequency for yield curve spreads S_2.

Generally, it is evident that callability and tax status are closely associated attributes of green bond yield spreads. More specifically, high-maturity and callable tax-exempt bonds, especially those issued at a premium, or federally taxable green bonds, especially when issued at par tend to have positive spreads. For the negative spreads, non-callable bonds, those issued at premium, or with low maturities tend to have negative spreads for both federally taxable and tax-exempt green bonds. A higher coupon rate emerges as a strong structuring attribute of negative spreads, particularly in federally taxable bonds. Maturity-related attributes become more relevant to yield curve spreads S_2. We will discuss the interpretation and policy implications of these findings next in Section 5.

4.5.3. Attribute associations based on bond's issuer sector

We identify the attribute associations of positive and negative spreads from a specific green bond issuer sector. We select issuer sectors with more than 100 green bonds, including General, Water, General Obligation, School District, Power, and Pollution.

Fig.s 16 and 17 present the most frequent attributes of positive and negative green bond spreads of certain issuer sectors. Accordingly, attributes related to the issued size and amount are frequent in (positive and negative) spreads together with maturity-related attributes

[30] We observe a conditional probability (confidence) of 100% (refer to subsection 4.2) when considering $S_1(+)$. This indicates that there are no bonds with negative spreads for federally taxable green bonds. However, since the same measure for $S_2(+)$ is not precisely 100%, we lower the support threshold for rules to identify attributes associated with $S_2(-)$ within this tax status. Thus, we utilize the $supp\_conf$ measure to identify the most important rules.

(including Active years, maturity_OID, and remaining years to maturity). Credit rating is frequent among green bonds with positive spreads in the Water and Pollution sectors and for negative spreads in the General and Water sectors. Tax is common in the Energy, Pollution and Utilities sectors, while callability is a dominant attribute mostly for negative spreads in School District, Pollution, General Obligation, and Utilities. Specifically, in the Power, Utilites, and Pollution sector, self-reported bonds and financing type (refund or new money) are the most frequent attribute with negative spreads.

Thus, green bond yield spreads based on issuer sectors are associated with the classical tax and callability attributes, yet credit rating, issued amount, and maturity related attributes are also critical, especially for negative spreads.

4.5.4. UOP-based attribute associations

Note that different sectors are issuing green bonds with various UOPs.[31] For a more complete assessment, we also examine the attribute associations of green bond yield spreads of different UOPs. The definitions of the UOP used in our analysis are summarized in Appendix K. Fig.s 18 and 19 show the attributes of positive and negative spreads for different UOPs, for the spreads S_1 and S_2, respectively.

We find that Green Purpose is the most frequent UOP across sectors, appearing more often in positive spreads, except in the Power and School District sectors. In the General, Water, and General Obligation sectors, Green Purpose is prevalent in both positive and negative spreads, though it appears more frequently in positive spreads. In contrast, the General Obligation sector shows a notable trend, with Current Refunding dominating negative spreads and Green Purpose being less frequent in positive spreads.

In the School District sector, School Improvements is the most common UOP, significantly more frequent in positive spreads. The Power sector shows Electricity Lights and Power

[31]Different sectors have varying environmental impacts, affecting the environmental benefits associated with green bonds. However, the UOP indicates how funds raised through green bonds will be used, providing clarity on the specific environmental projects or activities financed by the bonds. The UOP information improves transparency and accountability, helping investors assess the environmental impact of green bond projects. From an investment point of view, the UOP and issuer sector may also impact the risk of default and repayment. Investigation of these attributes can provide investors with valuable insights for their investment decisions (Benlemlih et al., 2023; Russo et al., 2021).

Improvements[32] as the dominant UOP, with a higher share in positive spreads. In the Pollution and Utilities sectors, refunding-related UOPs (Current Refunding and Refunding Notes) are more frequent in negative spreads, while Green Purpose has a smaller presence in positive spreads across both sectors.

5. Interpretation of findings and financial implications

Screening practices are integral to identifying the structural attributes of green bonds that influence their yields relative to risk-free benchmarks. By analyzing critical attributes, such as tax status, pricing strategy, callability, maturity, coupon rates, UOP, and issuer sector, investors and issuers can make informed decisions that align with both financial and environmental objectives. Based on empirical evidence from our investigations and associated studies, this section elaborates on the financial interpretations and implications of these attribute associations and their sectoral dynamics.

5.1. Tax Status

Tax status is one of the most influential attributes shaping green bond spreads, including their extreme values. Taxable municipal bonds pay interest income subject to federal and/or state taxes, whereas tax-exempt bonds offer federal and sometimes state tax exemptions, appealing to high-tax bracket investors. These differences significantly shape the appeal of green bonds for different investor profiles and yield environment preferences for issuers (Perlovsky and DeMarco (2018)).

Empirical results from our analysis indicate that taxable bonds are typically associated with positive spreads, particularly for long-maturity bonds, as investors in lower tax brackets or tax-advantaged accounts (e.g., pension funds) prioritize pre-tax yields over tax savings, especially in high interest rate environments. Conversely, tax-exempt bonds exhibit negative spreads, driven by a higher demand from high-net-worth investors seeking after-tax returns (Partridge and Medda (2020); Baker et al. (2022)).[33] This trend is particularly evident in sectors such as Water and General, where tax-exempt bonds dominate issuance (Environmental

[32]ELEC. LT. & PWR. IMPTS

[33]These findings are presentted in Section 4.2 and Figs. J.1-J.2.

Finance (2023)).[34]

The tax status often interacts with coupon rates and maturity. We find that taxable green bonds in lower coupon ranges and tax-exempt bonds in higher coupon ranges and longer maturities are generally associated with positive spreads.[35] Tax-exempt bonds with longer maturities and higher coupon rates align with buy-and-hold investors optimizing after-tax returns. To attract high-net-worth investors, tax-exempt bonds offer higher coupons to compensate the lower pre-tax yields. In contrast, taxable bonds typically offer lower coupons to offset the reduced after-tax investors' returns. Also, taxable bonds with shorter maturities may appeal to institutions seeking liquidity rather than tax benefits.

For issuers, tax status plays a strategic role in enabling access to diverse investor pools. Taxable bonds provide flexibility to fund projects that may not qualify for tax-exempt status under federal guidelines, such as private activity bonds or infrastructure initiatives with mixed-use benefits (Environmental Finance (2023)). In addition, taxable bonds attract international buyers or entities less sensitive to U.S. tax considerations, while tax-exempt bonds align with domestic investors focused on environmental and financial alignment often allow them to secure financing at a lower cost of capital. Furthermore, larger issuance sizes with well-structured coupon rates can enhance liquidity and attract diverse investor profiles, reinforcing the appeal of green bonds in competitive debt markets.

The choice of tax status impacts not only the spreads, but also the long-term value proposition of green bonds. Tax-exempt green bonds align particularly well with environmentally focused projects, offering investors a pathway to support sustainable initiatives while optimizing after-tax returns. This dual mandate of achieving financial performance and driving environmental impact underscores the critical role of tax-exempt bonds in aligning capital

[34]Based on U.S. tax-exempt municipal bonds, (Larcker and Watts, 2020) find insignificant greeniun in matched pairs of green and non-green bonds until 2018, see also (Karpf and Mandel, 2018). This result is based on greenium which contains targeted informational content compared to our more broad spread measure.

[35]The importance of coupon rates emerges more prominently when controlling for tax status and callability, which often act as confounding variables (see Figs. 14– 15 and Table 6). This phenomenon occurs when two variables are marginally associated due to their mutual dependence on a third variable (the confounding variable). By conditioning on the confounding variable, the marginal association between the original two variables is removed, and their independent effects can be identified. Our analysis also shows that the tenor-specific spread S_1 is highly correlated with coupon rates, while the yield curve spread S_2 demonstrates weaker associations.

markets with sustainability goals (International Capital Market Association (2018)).

5.2. *Pricing Strategy*

The pricing strategy in the primary market plays a pivotal role in shaping green bond spreads. We find that bonds issued at par often exhibit positive spreads, reflecting favorable pricing relative to risk-free benchmarks. Bonds issued at a premium typically show negative spreads due to oversubscription and increased demand (see Section 4.2).

The issuance of green bonds at par or premium often reflects market dynamics, including oversubscription and excess demand over supply at issuance. Premium issuance, a phenomenon highlighted in Baker et al. (2022), reflects strong investor confidence in green bonds. This "greenium" effect, where investors accept lower yields for sustainable investments as they prioritize environmental benefits over incremental yield advantages. This effect is particularly prevalent in sectors such as Renewable Energy and Power. Furthermore, oversubscription rates, highlighted in Environmental Finance (2023), provide additional evidence of the strong demand for green bonds, which contributes to the premium issuance pricing.

The premium pricing has implications that vary with bond's maturity. For short-maturity green bonds, the premium roll-down effect may not have time to materialize, resulting in negative spreads. Issuers of longer-maturity green bonds may leverage excess demand to extract higher premiums, potentially related to negative spreads (see Fig. J.1).

While premium-issued bonds align with ESG objectives, they require careful assessment of long-term value propositions, particularly for short maturities where roll-down effects may not materialize. For issuers, premium issuance reduces the cost of capital, but may exclude yield-sensitive investors, necessitating a balance between pricing optimization and market accessibility. As noted in Baker et al. (2022), the decision to price green bonds similarly to conventional bonds, despite demand-driven premiums, reflects broader market expectations for transparency and fairness.

5.3. *Callability, Maturity, and Duration*

Callability, maturity, and duration often interact in the way they relate to spread dynamics. Callable bonds, which allow issuers to redeem bonds before maturity, are typically associated with positive spreads due to the embedded option risk and insurance provision.

Non-callable bonds, on the contrary, exhibit narrower spreads as they provide greater certainty to investors, enabling the mitigation of short-term risks (Baker et al. (2022)).[36]

Longer maturities amplify the importance of callability and duration. Callable bonds dominate longer maturities, offering issuers flexibility to refinance under favorable conditions, while investors demand higher yields to offset early redemption risks. Callability in long-duration bonds is used to manage funding uncertainties (Environmental Finance (2023)).

Duration effects are particularly significant during periods of monetary policy change. Longer durations amplify spread dynamics, especially when the yield curve deviates from flatness, as shown in Fig. D.2. Callable bonds with extended durations often demand higher yields, while non-callable bonds with shorter durations offer stability and narrower spreads (Partridge and Medda (2020)).

The interaction between maturity and green bond attributes has broader implications for investors and issuers. For investors seeking stable cash flows, short-maturity bonds with limited optionality may provide better predictability and alignment with liquidity needs. However, investors with long-term horizons can capitalize on higher spreads associated with long-maturity callable bonds while supporting sustainable infrastructure and ESG-aligned projects. Issuers can leverage longer maturities to align debt repayment schedules with the lifespan of green projects, such as renewable energy installations or water management systems (Climate Bonds Initiative (2024, 2015)).

Sector-specific trends also shape these attributes. In the Water sector, longer maturities align with project lifespans, while the Power sector often issues shorter-term callable bonds to maintain operational flexibility . Investors must assess the likelihood of early redemption, while issuers leverage these attributes to balance flexibility and cost efficiency.

5.4. UOP and Issuer Sector

The Use of Proceeds (UOP) and the issuer sector also reveal significant structural associations with green bond spreads. In line with Zerbib (2019) and Bhanot et al. (2022), attributes such as credit ratings and issue sizes are particularly influential.[37] Higher-rated

[36] see Fig. J.1 and Fig. 14.

[37] Zerbib (2019) identify low credit rated corporate green bonds or bonds in the financial sector exhibiting negative yield spreads.

bonds (e.g., "A" and "AA+") in General and Water sectors are more commonly associated with negative spreads, reflecting reduced credit risk and greater pricing efficiency (see Fig. 16). Higher-rated bonds typically reflect stronger issuer credibility, thereby mitigating default risks and leading to lower yield spreads and attract investors seeking lower-risk investments.

Furthermore, issue size plays an increasingly prominent role in explaining both positive and negative spreads. Larger issuance sizes are often linked with enhanced liquidity, which is particularly evident in the Power sector. Liquidity considerations are paramount for institutional investors, as larger issues not only facilitate trading but also reduce the liquidity premium, contributing to narrower spreads. Research from Environmental Finance (2023) highlights how larger issuances of green bonds in the Power sector often align with UOPs related to electricity generation, such as "ELEC. LT. & PWR. IMPTS." These specific UOPs attract environmentally conscious investors, emphasizing the alignment between project objectives and investor mandates (see Fig. 18).

A distinctive feature of the Power sector is the prevalence of self-reported green bonds with negative spreads. While these bonds present attractive investment opportunities, their self-reported nature necessitates a thorough evaluation of underlying projects. Investors must critically assess whether the projects truly align with green objectives or risk being associated with greenwashing. For issuers, maintaining transparency and robust reporting standards is essential to sustaining investor confidence and demand for green bonds.

Given the sector-specific variations in credit ratings, issue sizes, and UOPs, investors should consider diversifying portfolios across multiple sectors and issuers. This approach not only mitigates sector-specific risks but also leverages the unique spread dynamics of different sectors, enhancing the overall risk-adjusted return of green bond investments.

6. Conclusion

Our study delves into the evolving and complicated landscape of green bond markets, particularly focusing on modelling spreads of green bonds and then identifying association attributes of the Californian municipal green bond spreads from a screening perspective. To address the shortcomings of traditional bond matching-based spread methods, we introduce two novel measures of green bond spreads based on the YTM and their term structure. We find that while green bond spreads in California are, on average, positive, they reach negative levels after 2022. The screening analysis reveals tax status, pricing strategy, and maturity as key attributes of positive spreads, while negative spreads exhibit more complex interactions with attributes such as spread and yield on issuance and callability. Yield curve spreads (based on the YTM term structure) are typically associated with duration, maturity, and callability.

These results demonstrate the importance of screening practice in green bond markets to navigate its complexities regarding its integration in current financial markets, and its implications in terms of policy and decision-making in asset management. Investors should consider green bonds not as a replacement for conventional bonds, but as a means to diversify their portfolios and capitalize on new investment opportunities. Positive spreads are related to specific bond attributes, such as tax status and pricing strategy, indicating potential investment opportunities. However, investors must tailor their investment decisions based on tax implications. Effective structuring of bond design and offerings is also essential for issuers. These innovative instruments offer issuers the opportunity to diversify their debt holder portfolio (Zerbib (2019)). Understanding investor preferences also allows for the tailoring of bond offerings to attract investors and secure better pricing.

Lastly, sectoral trends play an important role in shaping bond spread behavior. Considering Issuer sectors and UOPs, the role of credit rating, issued amount, and the green labels of the underlying projects becomes more evident. The Power sector exhibits unique characteristics, with self-reported bonds, higher credit ratings, larger issue sizes, and specific UOPs related to electricity generation being more prevalent. These factors contribute to higher demand, which increases prices when the scarcity of such instruments in the primary and secondary markets is significant relative to demand, thereby decreasing yields and reducing spreads. We demonstrate that such dynamics are not a universal attribute of green bond markets; instead, there is measurable and distinct heterogeneity across green bond market instrument types. This variability is more effectively isolated and studied through our proposed approach, which is not as readily captured by traditional matching methods in green bond settings.

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Contributions

MHS: Conceptualization, Data Curation, Formal Analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – Original Draft, Writing – Review & Editing
MC: Investigation, Methodology, Software, Validation, Writing - Original Draft, Writing - Review & Editing
CSN: Conceptualization, Formal Analysis, Investigation, Methodology, Project Administration, Supervision, Validation, Visualization, Writing - Original Draft, Writing - Review & Editing
GWP: Conceptualization, Data Curation, Investigation, Methodology, Formal Analysis, Supervision, Visualization, Validation, Writing - Original Draft, Writing - Review & Editing
KAR: Conceptualization, Data Curation, Formal Analysis, Methodology, Supervision, Writing – Review & Editing

References

Agrawal, R., Imieliński, T., Swami, A., 1993. Mining association rules between sets of items in large databases, in: Proceedings of the 1993 ACM SIGMOD international conference on Management of data, pp. 207–216. doi:10.1145/170035.170072.

Baker, M., Bergstresser, D., Serafeim, G., Wurgler, J., 2022. The pricing and ownership of US green bonds. Annual Review of Financial Economics 14, 415–437. doi:10.1146/annurev-financial-111620-014802.

Benlemlih, M., Jaballah, J., Kermiche, L., 2023. Does financing strategy accelerate corporate energy transition? Evidence from green bonds. Business Strategy and the Environment 32, 878–889. doi:10.1002/bse.3180.

Bhanot, K., Combs, C., Patel, R., 2022. Are there different shades of green? The "greenium" in municipal power bonds. The Journal of Fixed Income 31, 84–99. doi:10.3905/jfi.2022.1.129.

Bour, T., 2019. The green bond premium and non-financial disclosure: Financing the future, or merely greenwashing. Master's thesis, Maastricht University, Maastricht, The Netherlands https://finance-ideas.nl/wp-content/uploads/2019/02/msc.-thesis-tom-bour.pdf.

Brennan, M., MacLean, C., 2018. Growing the U.S. green bond market: Volume 2: Actionable strategies and solutions. Milken Institute Financial Innovations Lab. https://www.treasurer.ca.gov/growing-the-u.s.-green-bond-mkt-vol2-final.pdf.

California Green Bond Market Development Committee, 2023. California Green Bond Market Development Committee: Recommended Approach to Municipal Green Bond Disclosure. Technical Report. California Green Bond Market Development Committee. https://www.climatebonds.net/certification.

Caramichael, J., Rapp, A.C., 2024. The green corporate bond issuance premium. Journal of Banking & Finance 162, 107126. doi:10.1016/j.jbankfin.2024.107126.

CBI, C., 2023. Reports and resources. https://www.climatebonds.net/resources/reports.

Cecchetti, S.G., Hooper, P., Kasman, B.C., Schoenholtz, K.L., Watson, M.W., 2007. Understanding the evolving inflation process, in: U.S. Monetary Policy Forum, pp. 5–23. https://www.princeton.edu/~mwatson/papers/USMPF_Report_July_2007.pdf.

Cestau, D., Hollifield, B., Li, D., Schürhoff, N., 2019. Municipal bond markets. Annual Review of Financial Economics 11, 65–84. doi:10.1146/annurev-financial-110118-123034.

Chang, X., Hu, X., Shen, R., 2024. Local political preferences and green municipal bonds. Available at SSRN: https://ssrn.com/abstract=4973065.

Chen, Z., Mao, C.X., Wang, Y., 2010. Why firms issue callable bonds: Hedging investment uncertainty. Journal of Corporate Finance 16, 588–607. doi:10.1016/j.jcorpfin.2010.06.008.

Chiang, J., 2023. Growing the U.S. green bond market. Volume 1: The barriers and challenges. California State Treasurer. https://www.treasurer.ca.gov/greenbonds/publications/reports/green_bond_market_01.pdf.

Climate Bonds Initiative, 2015. Scaling up Green Bond Markets for Sustainable Development. Public Sector Guide. Climate Bonds Initiative. https://www.climatebonds.net/files/files/GB-Public_Sector_Guide-Final-1A.pdf.

Climate Bonds Initiative, 2024. Sustainable Debt Market Summary Q1 2024. Market Report. Climate Bonds Initiative. https://www.climatebonds.net/files/reports/cbi_mr_q1_2024_01e_1.pdf.

Doran, M., Tanner, J., 2019. Critical challenges facing the green bond market. London: Baker McKenzie. https://www.bakermckenzie.com/-/media/files/insight/publications/2019/09/iflr--green-bonds-%28002%29.pdf.

Environmental Finance, 2023. Municipal Green Bond Yield Behaviour. Available online: https://www.environmental-finance.com.

Falch-Monsen, K., Linnestad, M.J., 2024. I Can See Your Green Halo: Exploring the Role of Green Bond Issuance, Environmental Transparency, and Green Preferences on the Cost of Debt in European Markets. Master's thesis. Norwegian School of Economics. https://hdl.handle.net/11250/3158923.

Fang, F., Si, D.K., Hu, D., 2023. Green bond spread effect of unconventional monetary policy: Evidence from China. Economic Analysis and Policy 80, 398–413. doi:10.1016/j.eap.2023.08.019.

Fatica, S., Panzica, R., Rancan, M., 2021. The pricing of green bonds: are financial institutions special? Journal of Financial Stability 54, 100873. doi:10.1016/j.jfs.2021.100873.

Febi, W., Schäfer, D., Stephan, A., Sun, C., 2018. The impact of liquidity risk on the yield spread of green bonds. Finance Research Letters 27, 53–59. doi:10.1016/j.frl.2018.02.025.

Flammer, C., 2021. Corporate green bonds. Journal of Financial Economics 142, 499–516. doi:10.1016/j.jfineco.2021.01.010.

Hachenberg, B., Schiereck, D., 2018. Are green bonds priced differently from conventional bonds? Journal of Asset Management 19, 371–383. doi:10.1057/s41260-018-0088-5.

Hahsler, M., Buchta, C., Gruen, B., Hornik, K., 2023. arules: Mining Association Rules and Frequent Itemsets. R package version 1.7-7 https://CRAN.R-project.org/package=arules.

International Capital Market Association, 2018. Green Bond Principles: Voluntary Process Guidelines for Issuing Green Bonds. Guidelines. ICMA. https://www.icmagroup.org/assets/documents/regulatory/green-bonds/green-bonds-principles-june-2018-270520.pdf.

Kapraun, J., Latino, C., Scheins, C., Schlag, C., 2021. (in)-credibly green: which bonds trade at a green bond premium?, in: Proceedings of Paris December 2019 Finance Meeting EUROFIDAI-ESSEC. https://dx.doi.org/10.2139/ssrn.3347337.

Karpf, A., Mandel, A., 2018. The changing value of the 'green' label on the U.S. municipal bond market. Nature Climate Change 8, 161–165. doi:10.1038/s41558-017-0062-0.

Larcker, D.F., Watts, E.M., 2020. Where's the greenium? Journal of Accounting and Economics 69, 101312. doi:10.1016/j.jacceco.2020.101312.

Lombardi Netto, A., Salomon, V.A.P., Ortiz Barrios, M.A., 2021. Multi-criteria analysis of green bonds: Hybrid multi-method applications. Sustainability 13, 10512. doi:10.3390/su131910512.

Monasterolo, I., Raberto, M., 2018. The EIRIN flow-of-funds behavioural model of green fiscal policies and green sovereign bonds. Ecological Economics 144, 228–243. doi:10.1016/j.ecolecon.2017.07.029.

OECD, 2017. Barriers, policy actions and options for green bond market development and growth, in: Mobilising Bond Markets for a Low-Carbon Transition. OECD Publishing, Paris. doi:10.1787/9789264272323-5-en.

Partridge, C., Medda, F., 2018. Green premium in the primary and secondary U.S. municipal bond markets. Available at SSRN: https://ssrn.com/abstract=3237032.

Partridge, C., Medda, F.R., 2020. The evolution of pricing performance of green municipal bonds. Journal of Sustainable Finance & Investment 10, 44–64. doi:10.1080/20430795.2019.1661187.

Perlovsky, I., DeMarco, T., 2018. Overview of the taxable municipal market. Boston: Fidelity Capital Markets. https://www.fidelity.com/bin-public/060_www_fidelity_com/documents/fixed-income/retail-taxable-muni-white-paper-2018.pdf.

Russo, A., Mariani, M., Caragnano, A., 2021. Exploring the determinants of green bond issuance: Going beyond the long-lasting debate on performance consequences. Business Strategy and the Environment 30, 38–59. doi:10.1002/bse.2608.

Shinde, A.A., 2021. Green Bonds an investment tool for resilient future: Helping to achieve Circular Economy business models. Master's thesis. University of Waterloo. http://hdl.handle.net/10012/17676.

U.S. Environmental Protection Agency, 2024. Municipal bonds and green bonds. URL: https://www.epa.gov/statelocalenergy/municipal-bonds-and-green-bonds.

Zerbib, O.D., 2019. The effect of pro-environmental preferences on bond prices: Evidence from green bonds. Journal of Banking & Finance 98, 39–60. doi:10.1016/j.jbankfin.2018.10.012.

Zhang, R., Li, Y., Liu, Y., 2021. Green bond issuance and corporate cost of capital. Pacific-Basin Finance Journal 69, 101626. doi:10.1016/j.pacfin.2021.101626.