A term structure framework for green bond spreads and portfolio strategies

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Abstract

The term structure of green bonds plays an important role in determining pricing practices and informing green bond portfolio design. We introduce a novel green bond yield spread measure, derived from the term structure of yields to maturity embedding curve-based information into bond valuation. We screen structural attribute associations of green municipal bond curve-based spreads using Association Rule Learning and find that taxable green bonds with intermediate maturities and short durations are systematically linked to positive spreads. Screened green bond groups then inform the construction of tenor- and duration-based portfolios that deliver lower drawdowns and higher, more stable risk-adjusted returns relative to Treasury, particularly during periods of monetary tightening, while hybrid portfolios preserve most downside protection benefits. This superior performance is attributed to curve-level pricing and structural composition. The term structure framework develops profitable portfolio strategies to inform investors, issuers, and regulators in shaping transparent and efficient sustainable finance ecosystems.

Keywords: green bonds, municipal bonds, yield term structure, green bond yield spread, sustainable portfolios

JEL: C11, E43, E44, G12, Q51, Q56

1. Introduction

The green bond market has expanded rapidly over the past decade, moving from a niche financing instrument to a material segment of global fixed-income markets. The vast majority of green bonds are held by institutional investors, including pension funds, insurance companies, banks, and especially ESG-focused asset managers, with retail investors playing only a minor role, mostly via sustainable bond funds (International Finance Corporation, 2024). These investors allocate capital subject to duration targets, risk budgets, and liability constraints, and therefore assess green bonds relative to alternative fixed-income portfolios with comparable interest-rate exposures. Thus, they have been rapidly expanding their dedicated sustainable portfolios whose mandates are inherently portfolio-based rather than security-specific (Ehlers and Packer, 2017; CBI, 2024).[1] Most of the empirical literature though remains largely focused on security-level pricing differences. For long-horizon investors operating under liability, risk-budget, and benchmark constraints, the absence of portfolio-level evidence is particularly limiting, as investment relevance depends not on isolated yield differentials but on how green bonds perform when embedded in diversified fixed-income strategies (Pástor et al., 2021; Baker et al., 2022). This gap highlights the urgent need for frameworks that link green bond pricing to comprehensive screening mechanisms and, more importantly, to implementable portfolio construction grounded in term-structure information.

This paper addresses this critical knowledge gap in green bond portfolio management by first proposing a novel term-structure framework for measuring green bond yield spreads that explicitly embeds information across the entire yield curve into bond valuation. Rather than collapsing relative pricing to a single maturity point, the framework recovers curve-level pricing information within structurally homogeneous partitions and values green bond cash flows using discount rates matched to their full term structure. Single-tenor matching implicitly assumes that bonds with the same stated maturity are comparable along the entire term structure. In practice, this assumption is violated in municipal markets, where sparse trading, heterogeneous coupon structures, different green use of proceeds, and embedded

[1] Global sustainable investment funds reached \$3.6 trillion in assets under management in 2024 (International Finance Corporation, 2024) and are motivated by climate mandates and ESG commitments to allocate capital to green assets.

call options cause bonds with identical maturities to load differently on the yield curve. A curve-to-curve comparison mitigates this mismeasurement by valuing each bond against the entire fitted term structure, thereby capturing pricing differences that arise from the full distribution of cash flows rather than from an arbitrarily chosen tenor. This approach aligns with modern term-structure asset pricing, which emphasizes that relative value and risk compensation are inherently curve-dependent and cannot be fully assessed at a single maturity (Cieslak and Povala, 2015; Green et al., 2010). By construction, the proposed spread measure is robust to sparse transaction data and is directly compatible with duration-targeted portfolio designs.

Second, this term-structure framework for green bond portfolio construction is paired with a systematic screening mechanism that identifies subsets of green bonds with distinct curve-level pricing behavior. This screening mechanism is based on a machine learning approach, the Association Rule Learning (ARL), thus it reduces heterogeneity, improves economic interpretability, and enables the construction of portfolios that maintain stable interest-rate exposure while rotating across attribute-defined bond groups. Consequently, portfolio applications are an integral part of the methodology (rather than an ancillary exercise), translating term-structure-based spread information into replicable investment strategies under realistic institutional constraints. A term-structure based green bond yield spreads and data-driven screening mechanism jointly guide green bond portfolio formation.

More specifically, we estimate daily term-structure-based green bond yield spreads for California green municipal bonds between 2020 and 2024. We find that the median curve-based green spread is initially positive at 0.48 percent in 2020, before steadily declining and persistently negative after 2022, with median spreads of approximately -0.23 percent in 2023 and -0.25 percent in 2024. In addition, the ARL screening exercise reveals that green bond characteristics including tax status, pricing strategy, callability as well as maturity and duration related features hold distinct associations with positive and negative curve-based green bond yield spreads. Notably, taxable green bonds with intermediate maturities and shorter duration as systematically associated with positive curve-based spreads.

We then leverage the ARL attribute-specific green bond groups to construct and evaluate performance of homogeneous, duration-targeted, and hybrid portfolios that blend screened green bonds with Treasury securities. Across all portfolio designs, structurally screened green bond portfolios consistently exhibit lower maximum drawdowns, smoother cumulative return paths, and more stable Sharpe and Sortino ratios relative to maturity- and duration-matched Treasury benchmarks. These benefits are especially pronounced in duration-targeted strategies, which deliver materially higher cumulative returns without increasing interest rate exposure. While Treasury portfolios rebound more rapidly after large drawdowns, screened green portfolios display a slower but more stable recovery, reflecting tighter post-2022 green bond spreads and elevated entry prices during the recovery phase. Hybrid portfolios further demonstrate that even partial green allocations preserve a substantial share of these downside protection benefits while improving liquidity. Based on our framework, these performance differences across portfolios are driven by curve-level pricing effects and attribute-based composition, rather than by excess exposure to interest-rate duration risk. This analysis underscores the central role of term structure information rather than pointwise yield differentials in designing robust fixed income green bond strategies.

The empirical literature remains largely focused on security-level pricing differences, offering limited guidance on how green bonds should be systematically screened, combined across maturities, and evaluated within duration-constrained portfolios. Our paper makes two fundamental contributions to these domains. First, in contrast to typical tenor-specific approaches (Partridge and Medda, 2018; Zerbib, 2019; Kapraun et al., 2021; Bhanot et al., 2022), we introduce a comprehensive and novel measure of green bond yield spreads embedding information from the entire term structure. Second, we propose an attribute-based screening process for green bond spread to inform duration-based construction of high performance/low risk green bond portfolios.[2] Most empirical studies on green bonds rely on matched-bond designs or regression-based comparisons at individual maturities, which are well suited to identify average pricing differences, but are not designed to support portfolio construction (Larcker and Watts, 2020; Bhanot et al., 2022). Because these methods

[2]A natural identification concern is whether the estimated curve-based spreads reflect tax treatment, credit risk, or liquidity premia rather than a distinct green preference. While the screening exercise does not claim causal identification of a greenium, partitioning by tax status and structural features, together with duration-matched portfolio tests, is designed to separate measurement improvements from systematic risk compensation.

do not recover term-structure pricing information, they offer limited insight into how green bonds can be combined across maturities, how duration-neutral portfolios can be formed, or how portfolio performance evolves under realistic rebalancing schemes. This gap has been increasingly recognized in the broader sustainable finance literature, where recent surveys highlight the scarcity of portfolio-based evidence in fixed income relative to the growing number of security-level greenium studies (Marín-Rodríguez et al., 2023). Pástor et al. (2021) also shows that sustainability preferences and hedging motives affect expected returns only insofar as they operate through portfolio allocation and risk sharing rather than individual securities alone.

These limitations are apparent in illiquid fixed-income markets. Evidence on price formation shows that trading frictions and intermittent trading complicate inference from observed prices, motivating valuation approaches that remain informative when transaction data are sparse (Green et al., 2010). Related work in corporate and municipal bond markets[3] highlights that liquidity provision and dealer balance-sheet constraints impact execution costs and market functioning, further underscoring why portfolio evaluation cannot rely solely on spot comparisons at a single maturity or trade (Bessembinder et al., 2018). In green bond markets, these frictions interact with ESG-motivated demand, where strong investor preferences, scarcity of issuance, and tax considerations can compress yields across segments of the entire yield curve (Flammer, 2021; Baker et al., 2022). Our proposed term-structure-based green bond yield spread approach and the attribute-based screening for green bond portfolio construction address these limitations to offer robust green portfolio risk management tools. We demonstrate a substantial economic magnitude of the daily curve-based green spread, with interquartile ranges on the order of 0.30 to 0.50 percent and enable daily green portfolio evaluation, despite infrequent municipal market trading, which occurs on average only about ten days per month.

[3] Corporate issuers account for the bulk of global green bond supply—typically between one-half and two-thirds of annual issuance (London Stock Exchange Group, 2025; Climate Bonds Initiative, 2024). Sovereign governments represent the next largest segment (around 20% of issuance in 2024), followed closely by supranational and agency issuers (Climate Bonds Initiative, 2024). By contrast, municipal issuers remain a relatively small component of the market; for example, local governments raised only about $23 billion in green bonds globally in 2024 (Climate Bonds Initiative, 2024).

Furthermore, typical curve-based approaches rely on issuer- or rating-level fitted curves (Wang et al., 2026; Andreasen et al., 2019), which are well suited to liquid markets but become unreliable in municipal settings characterized by infrequent trading and heterogeneous bond features. In such environments, curve estimates are often driven by a small number of observations at isolated maturities, amplifying tenor-specific noise. Our partitioned curve-to-curve framework mitigates this issue by pooling information across comparable structures while preserving maturity resolution across the entire term structure. Thus, the novelty of the proposed framework does not lie in the curve fitting per se, but in the use of curve-to-curve valuation as a measurement device for relative pricing. By valuing each bond against the entire fitted term structure, the approach reduces sensitivity to local yield distortions arising from optionality, coupon effects, and uneven liquidity along the curve.

The remainder of the paper is organized as follows. Section 2 reviews term-structure methods and fixed-income portfolio construction in the green bond pricing literature. Section 3 describes the data and develops the term-structure-based green bond yield spread methodology. Section 4 presents the ARL screening results and examines the structural attributes associated with positive and negative green bond yield spreads. Section 5 translates the term-structure and screening results into implementable portfolio strategies, evaluating homogeneous, hybrid, and duration-targeted green bond portfolios relative to Treasury benchmarks. Section 6 concludes and discusses financial implications for portfolio design.

2. Literature review

This study advances the literature on green bond markets in two unexplored dimensions: the role of term structure in the valuation and screening of green bond yield spreads and in the construction of green fixed income portfolios.

2.1. The missing role of term structure in the valuation and screening of green bond spreads

A central theme in the green bond pricing literature is whether, and under what conditions, green-labeled bonds command a yield differential ("greenium") relative to comparable conventional bonds. Empirically, the dominant measurement strategy is point-wise: studies compare a green bond's yield (or yield spread) at a given date to that of a conventional bond or benchmark observed at a matched maturity (or closest available tenor). One strand of this literature relies on matched-bond designs and fixed-effects specifications to isolate green pricing effects by controlling for issuer, maturity, and time-specific characteristics. These approaches aim to minimise cross-sectional heterogeneity by comparing green and non-green bonds that are as similar as possible, often within the same issuer or narrow maturity buckets (Kapraun et al., 2021; Bhanot et al., 2022; Chang et al., 2024). A related strand employs regression-based adjustments, where green labels enter yield or spread regressions alongside controls for bond characteristics, liquidity proxies, and market conditions. These studies estimate an average greenium at specific maturities while accounting for observable risk factors, but still evaluate pricing differences on individual points of the curve (Berdiev, 2025; De Vincentiis and Abis, 2025; Dragotto et al., 2025).

This design is attractive because it is transparent and easily interpreted at a given maturity point, which facilitates comparability. For example, Zerbib (2019) estimates the yield differential using matching and regression adjustments in an international sample. Larcker and Watts (2020) exploit the institutional structure of the U.S. municipal market to compare nearly identical green and non-green issues by the same issuer on the same day, directly targeting a clean point-wise comparison. In corporate markets, Flammer (2021) studies "corporate green bonds" and documents how issuance relates to investor response and post-issuance environmental outcomes, motivating the role of investor preferences and certification in pricing. Evidence on issuance spreads continues to rely primarily on matched-sample and regression-based comparisons at issuance and in the cross section (Partridge and Medda, 2018; Caramichael and Rapp, 2024).

Although these point-wise and matched-maturity approaches are informative, they share a limitation that becomes crucial in municipal green bond markets, where instruments are heterogeneous (Cestau et al., 2019), trading can be episodic (Febi et al., 2018), and cash-flow structures (coupons, callability, and sinking features) imply that valuation depends on discounting across multiple future payment dates. Economically, term-structure information matters because the yield curve aggregates expectations and risk compensation across horizons, and shifts in its level, slope, and curvature alter relative valuations even when a bond's stated maturity is unchanged. Modern term-structure research emphasizes that forces beyond expected short rates, such as segmented demand and limited risk-bearing capacity, shape yields across maturities, reinforcing that "relative value" is inherently curve-dependent (Cieslak and Povala, 2015; Greenwood et al., 2024; Mitra and Xu, 2024). Consequently, a spread measure that collapses the comparison to a single tenor may miss economically relevant variation of green bond pricing across discount points, which is the variation that the proposed term-structure approach aims to preserve.

Green bond studies incorporate bond-level characteristics primarily for identification rather than screening. Zerbib (2019) uses issuer-level matching to estimate a small negative green premium, treating bond attributes as controls rather than classification tools. Larcker and Watts (2020) exploit quasi-identical green and non-green municipal bond tranches issued simultaneously by the same issuer and find no economically meaningful greenium once risk and cash flows are held constant. Flammer (2021) documents real and equity-market effects following corporate green bond issuance but finds no systematic yield advantage attributable to the green label after controlling for bond characteristics. Bhanot et al. (2022) show that green power bonds command a yield premium relative to other green municipal bonds when the use of proceeds is clearly identifiable, highlighting heterogeneity within the green bond universe rather than an unconditional greenium. Overall, while bond characteristics are central to spread estimation, the literature does not use them jointly as a screening mechanism to classify green bonds into economically distinct groups for portfolio construction. Recent fixed-income research shows that attribute-based sorting improves portfolio design in heterogeneous and illiquid markets by filtering securities according to structural risk exposures rather than pointwise yields (Bessembinder et al., 2018; Greenwood et al., 2024). The green bond literature lacks a systematic screening framework that uses bond characteristics to identify subsets with distinct spread behavior suitable for portfolio construction. This paper proposes attribute-based screening that supports duration-consistent portfolio analysis.

2.2. The role of term-structure-based green bond spreads for fixed-income portfolio construction

In industry and academic literature, portfolio design in bond markets is closely linked to term-structure risk management, as bond returns and risk premia vary systematically across maturities. Borup et al. (2024) document pronounced state-dependent predictability in bond returns across maturities and show that exploiting yield-curve information improves economic utility, highlighting the relevance of term-structure dynamics beyond average returns. Dubiel-Teleszynski et al. (2024) demonstrate that imposing economically meaningful restrictions on the market price of risk within dynamic term-structure models is essential for translating statistical predictability into out-of-sample portfolio gains. Randl et al. (2025) analyze international government bond portfolios and show that portfolio performance depends on exposure to term-structure risks, with substantial gains achievable by hedging unpriced yield-curve components rather than relying on naive duration-based strategies.

This term-structure dependence is particularly acute in less liquid markets, where observed transaction prices may be sparse and where portfolio rebalancing must rely on robust valuation inputs (Zerbib, 2019; Fatica and Panzica, 2024). While much of the green bond literature focuses on identifying and estimating a green pricing differential at the security level, considerably less attention has been devoted to understanding how such pricing information translates into investable portfolio strategies. From an asset-pricing perspective, the economic relevance of a green bond spread ultimately depends on whether it can be systematically harvested, managed, or offset within a diversified fixed-income portfolio. Empirical research in sustainable fixed-income markets has increasingly shifted the attention to understanding how green bonds perform within portfolios rather than solely as isolated securities. Silva et al. (2024) evaluate portfolio performance under climate policy uncertainty and show that green bond portfolios can outperform traditional and "black" bond portfolios conditional on climate risk, highlighting the importance of portfolio-level analysis in sustainable fixed-income investing. Abuzayed and Al-Fayoumi (2023) study diversification and hedging strategies involving green bonds alongside conventional asset classes and demonstrate that optimal portfolio allocations to green bonds can materially reduce portfolio risk and improve risk-adjusted returns. Marín-Rodríguez et al. (2023) provide a comprehensive review of the literature on the integration of green bonds into investment portfolios, identifying diversification, co-movements, and risk management as central themes, and explicitly call for more structured portfolio-oriented empirical frameworks.

Furthermore, green bond portfolio outcomes depend primarily on allocation design, maturity composition, and investor-level portfolio choices, rather than on average green premia. Swinkels and Yang (2022) demonstrates that green bond portfolios differ systematically from conventional fixed-income benchmarks in terms of maturity structure and market segmentation, making performance sensitive to how green exposure is allocated across the curve. Kapraun et al. (2021) show that pricing and risk characteristics vary with issuer credibility and bond features, implying that portfolio composition across issuers and bond types matters more than security-level yield differences. Finally, Li et al. (2025) provide fund-level evidence that green bond allocations affect performance and redemption risk, confirming that realized outcomes are driven by how green bonds are combined within portfolios, not by average yield effects alone.

Despite these advances, the literature largely treats portfolio formation as an ex post exercise applied to broad green bond universes, without a systematic mechanism for screening bonds ex ante based on their term-structure pricing behavior. Curve-level information has also not been exploited to classify green bonds into economically meaningful subsets associated with persistent behaviour across maturities. Thus, portfolio strategies remain disconnected from the underlying spread construction and from the term-structure forces that govern fixed-income risk exposure. This paper addresses this gap by integrating a term-structure-based spread measure with an attribute-driven screening framework, allowing the identification of green bonds with distinct curve-level pricing profiles that inherently allow for duration-consistent portfolio construction and evaluation.

3. Data description and yield spread calculation

3.1. Data Description

We use daily yields to maturity (YTM) of municipal green bonds issued in California[4] between 2020 and 2024, collected from the Bloomberg Information Services terminal.[5] The term-structure-based yield spread computations require bootstrapping of the yield curve of green bonds within certain partitions of similar characteristics, such as tax status and

[4] California is used for this study for several reasons: It has the most liquid green bond market in the U.S. offering a pool of green bonds with diverse structuring properties (California Green Bond Market Development Committee, 2023). It's characterised by a diverse range of issuers and industries that operate in a stable taxation system with a substantial overall volume of issuance, underscoring its scale and market maturity.

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

coupon. For a creditable analysis, a sufficiently large number of observations should be included in the bootstrapping exercise and thus we start our sample from 2020. We also collect information on 34 structuring attributes of these bonds, some numerical, such as spread at issuance, issued amount, maturity on issue date, and some categorical, including tax status, callability, and pricing type (at par or at premium). Appendix A details the full list of attributes.

In addition, we collect par yields of U.S. Treasury bonds from the U.S. Department of the Treasury, see U.S. Treasury Interest Rate Statistics. The U.S. Treasury provides a liquid, default-free term structure that isolates relative pricing effects at the curve level, allowing differences in municipal yields arising from tax treatment, credit risk, and liquidity to be examined through subsequent partitioning and attribute-based screening rather than embedded directly in the benchmark. Unlike inflation-adjusted (real) par yield curves, which embed inflation expectations, par yields enable a direct comparison of nominal yields without further adjustments. In the context of time series data expressed in monetary terms, inflation frequently acts as a primary driver and a significant source of volatility (Cecchetti et al., 2007).

3.2. Green bond yield spreads based on the term structure of YTM

We present a novel approach to compute green bond yield spreads using a comprehensive set of data points across the term structure of the yield curve that allows a curve-to-curve comparison on a daily basis. Incorporating the term structure of yield curves allows one to vary 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, this approach captures term-specific risk and return expectations.

Green bond yield spreads based on the term structure of YTM require 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. To construct comparable bootstrapped green bond curves, it is essential to separate green bonds with similar structural characteristics. Accordingly, we begin by partitioning the

California green bonds and then constructing the bootstrapped curves. In the last step, we extract the corresponding discounting spot rates from the bootstrapped curves to compute the associated green bond yield spreads.

Although this analysis focuses on the California municipal green bond market as one of the largest and most active sub-national green bond markets in the U.S. (CBI, 2019), illiquidity remains a pervasive challenge across green bond markets more broadly.[6] Our empirical approach is designed to accommodate sparse trading data, making the methodology applicable to other green bond markets facing similar liquidity constraints, as well as more actively traded corporate or sovereign green bonds.

3.2.1. Partitioning of green bonds (Step 1)

To improve the precision and reliability of discounting factors derived from observed yields in various terms, we systematically address variations in green bond prices and create partitions of bonds or grouping bonds with similar structural features. This partitioning process should include sufficient observations within the bond partitions to reliably perform the yield curve bootstrapping for each green bond daily.

We identify callability, coupon rate, and tax status as discriminatory structuring attributes of green bonds that exhibit clear patterns (clusters) in California's green bond YTM. Note that callability embeds issuer options that alter cash-flow timing and effective duration, generating systematic yield differences relative to non-callable bonds, as shown in the literature on callable bond pricing (Longstaff, 1992; Duffee, 1998). Coupon rate influences yield behavior through its interaction with duration, convexity, and reinvestment risk, producing persistent yield dispersion even among bonds with similar maturities (Amihud and Mendelson, 1991; Green, 1993). Tax status is a first-order determinant of yield levels in municipal bond markets, as differential tax treatment induces stable yield segmentation across investor clienteles (Green and Ødegaard, 1997; Chalmers, 1998). Consistent with this empirical evidence, Appendix C visually confirms that California green bond YTMs cluster distinctly along these three attributes, while comparable separation is not observed for other bond characteristics such as issuer industry, credit rating, market issue, and use of proceeds.

[6] Our sample contains 1,092,164 bond-day observations, representing 38.04 % of potential trading day observations. Bonds are observed on average 10.06 days per month.

To ensure balanced sample sizes across partitions, we consider nine partitions of green bonds with an optimal trade-off between the number of callable and non-callable bonds, their coupon rate intervals, and tax status. Coupon breakpoints are based on the quartiles of the coupon distribution for callable and non-callable bonds, rounded for precision (see Appendix C for details). We use the abbreviation FTSE for *Federal Taxable and State Tax Exempt* bonds, and TE for all tax-exempt bonds,[7] with *Federal and State Tax Exempt* bonds comprising the majority of this category. Table 1 summarizes the nine partitions of green bonds and their descriptive summary. These partitions reflect 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 corresponding green bond cash flows.

3.2.2. Constructing daily yield curve via bootstrapping (Step 2)

In the yield curve spread calculation approach, we estimate bootstrap curves on a daily basis within bond partitions, as discussed in the previous section. 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 green bond bootstrap curves with three-knot points at the 25th percentile (Q1), median, and 75th percentile (Q3) of the maturity distribution within each partition. Green bond observations are also unevenly distributed across maturities, further motivating the use of linear (B1) splines to avoid overfitting in sparse regions. However, Treasury par yields are observed at fixed tenors with no missing data permitting smooth cubic (B3) spline interpolation.[8]

Figure 1 displays an illustrative example of green bond B1-spline bootstrap curves in California on 2022-05-23 (fitted to the partitions outlined in Step 1) with the overall accuracy of the fitted bootstrap curves being satisfactory. The complete bootstrapping procedure and

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

[8]For a B-spline of order 1 with three knots, a minimum of four observations is required for identifiability, although a larger number (e.g., 6–10) is preferable for stable estimation. On days where the number of available observations fell below this threshold, we carried forward the most recently estimated curve to ensure continuity of the functional representation

specifications for extracting zero-coupon equivalent yields are detailed in Appendix C.

3.2.3. Determination of spot rates for discounting and computation of yield curve spreads (Step 3)

Our 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.

Let consider on day t, green bond i with face value of FV_i,[9] coupon frequency of m_i (payments per year), coupon payments C_i, and annualized quoted $YTM^G_{i,t}$, which has remaining number of payments N, $\mathbb{I}(\cdot)$ an indicator function to identify the timing of coupon payments, and $\tau_{i,n}$ be the remaining year fraction to the n^{th} payment. Then, the green equivalent Zero-Coupon Bond Yields to Maturity, denoted as $YTM^{(GZCB)}_{i,t}$, is computed as follows:

$$YTM^{(GZCB)}_{i,t} = \left[\frac{1}{\widetilde{FV}_i} \left(\sum_{n=1}^{\hat{N}} \frac{C_i \mathbb{I}(\tau_{i,n})}{(1 + (\frac{r^{(G)}_t(\tau_{i,n})}{m_i}))^n} + \frac{FV_i}{(1 + (\frac{r^{(G)}_t(\tau_{i,N})}{m_i}))^N} \right) \right]^{-\frac{1}{N}} - 1, \qquad (1)$$

where $r^{(G)}_t(\tau_{i,n})$ and $r^{(G)}_t(\tau_{i,N})$ represent the yields extracted from the bootstrapped green yield curves (produced in step 2) corresponding to their respective terms $\tau_{i,n}$ and $\tau_{i,N}$, and $n, \ldots, N$ are the corresponding tenors considered on day t. This approach differentiates itself from other green bond yield spread methods that discount green bond cash flows with the same yield to maturity (Zerbib, 2019; Bhanot et al., 2022; Baker et al., 2022; Sehatpour et al., 2024).

Next, we extract the corresponding rates from the U.S. Treasury par yield curves on day t, to compute the equivalent zero-coupon reference rate that corresponds to the tenors of cashflows of the green bond i. 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. Thus, the reference

[9] $\widetilde{FV}_i$ needs to be adjusted for bonds that pay both the final coupon and the principal at maturity. This adjustment is needed, as when the last coupon coincides with maturity, it ensures the equivalent zero-coupon bond accurately reflects the bond's full cash flow structure.

equivalent Zero-Coupon Bond Yield to Maturity, $YTM_{i,t}^{(RZCB)}$, can be computed as follows:

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

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 in day t. The difference of these two zero-coupon yields computes the green bond yield spreads of this specific bond, as

$$S_{i,t} := YTM_{i,t}^{(GZCB)} - YTM_{i,t}^{(RZCB)}. \tag{3}$$

To calculate the equivalent green and reference YTM, we use 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. Following this process, we compute yield spreads for all available green bonds on a daily basis. The full technical details of the green bond yield spread computations are presented in Appendix D.

Figure 2a depicts the daily median of yield curve spread $S_{i,t}$, in California between 2020 – 2024. Figure 2b shows the distributions of the spreads, and Table 2 provides a statistical summary of spreads between 2020 and 2024. The distribution of California green bond yield spreads over 2020–2024 reveals a clear temporal transition from positive to negative values, reflecting a structural evolution in market pricing behavior. In 2020, the spreads were predominantly positive (mean = 0.44, median = 0.48), indicating that green bonds initially traded at a higher yield relative to the comparable benchmark. This pattern is consistent with the early-stage nature of the market, when limited liquidity and information asymmetry contributed to higher required returns. From 2021 onward, the spreads declined markedly, turning negative by 2023 (median = –0.23) and remaining so through 2024 (median = –0.25). The shift from positive to negative spreads suggests a growing investor preference for environmentally sustainable instruments, leading to a premium by which investors accept lower yields in exchange for environmental benefits and reputational value. This transition also coincides with the 2022 interest rate hike, from the exceptionally low rates of the COVID-19 period to the post-2021 tightening cycle. During this period, green bonds' stable investor base provided relative price support compared to duration-equivalent Treasuries experiencing forced selling (see Appendix D). The increasing standard deviation (from 0.25 in 2020 to 0.37 in 2023) points to rising heterogeneity across issuers and bond characteristics, possibly due to differences in project types (e.g. Use of Proceeds (UOP)),[10] certification credibility, and maturity structures. In the entire sample, the mean spread of –0.03 is moderate but persistently lower yield, which indicates that the California green bond market has matured into a pricing environment that systematically rewards sustainability-oriented debt instruments.

4. Attributes associations of green bonds spreads

In this section, we present a screening process using ARL to identify and analyze the attribute associations of green bond yield spreads (Agrawal et al. (1993)). This method detects statistical associations (not cause-and-effect mechanisms) and has been useful in analysing market baskets, customer segmentation, and recommendation systems (Srivastava et al., 2024; Yang and Wu, 2025; Huang et al., 2023) and green bond screening (Sehatpour et al., 2024). ARL is employed as a complementary screening tool rather than as a predictive classification model. Unlike logit/probit or supervised machine-learning approaches, ARL is designed to identify transparent, multi-attribute co-occurrence patterns that are directly interpretable and easily translated into portfolio construction rules, which is central to the paper's applied objective.

ARL identifies frequent itemsets, and defines co-occurrence rules in terms of support, confidence, and lift. Support reports the appearance frequency of itemsets. Confidence evaluates the conditional probability of appearance an itemset – the appearance frequency of the second item when the first one is present. Lift gauges this relationship in terms of the two items been unrelated: for a value above one the items occur together more than expected, for a value around one then there is no real link between the items, and for a value below one they occur together less than expected.[11] We also use the Apriori algorithm to identify

[10] A full definition of the UOP for the green bonds in our dataset is presented in Appendix A.

[11] In line with Sehatpour et al. (2024), we provide the following definitions. For any itemsets A and B, the support, confidence, and lift of the association $A \Rightarrow B$ are defined respectively as: Support$(A \Rightarrow B) = \frac{|A \cap B|}{N}$, Confidence$(A \Rightarrow B) = \frac{|A \cap B|}{|A|}$, Lift$(A \Rightarrow B) = \frac{|A \cap B|}{|A| \cdot |B|}$, where N denotes the total number of transactions (observations) and $|\cdot|$ represents the cardinality of the corresponding set.

frequent itemsets based on a minimum support threshold, and to generate association rules from these itemsets using a minimum confidence threshold. Methodological details on the ARL framework and the technical aspects of the Apriori algorithm, data labelling process and associated thresholds are presented in Appendix E.[12]

To mitigate concerns related to multiple testing and data mining, the analysis relies on conservative support and confidence thresholds and focuses on stable, first-order rules that persist across time periods, with ARL results used for screening and interpretation rather than for statistical inference or standalone prediction.

We next report the first-order attribute associations[13] of positive and negative green bond spreads. We also investigate the temporal consistency of their strongest attribute associations, where the monthly median of each bond's spreads serves as a representative central measure for the analysis.

4.1. Attribute associations for positive green bond spreads

We identify attribute associations of positive spreads using single-rule attributes—what we term *first-order* rules. Table 3a presents the support, confidence and lift metrics for these association rules, as ranked by confidence.

We find that federal taxable status is the dominant attribute associated with positive green bond yield spreads with a confidence of 0.966 and support of 0.155. This indicates that 96.6% of federally taxable green municipal bonds display positive spreads, comprising approximately 15.5% of the California green bond universe. The lift value of 2.050 confirms the strength of this association, suggesting that these bonds occur with positive spreads more than twice as frequently as would be expected under independence. The second-ranked association identifies at-par pricing, with 94.7% of such bonds linked to positive spreads (support of 0.149). This pattern reflects favorable initial pricing dynamics that persist throughout the bond's life when evaluated against the full Treasury curve structure. The term structure framework captures how taxable and at-par green bonds maintain their

[12]The contribution of these attributes to the yield spread variations has been further evaluated by using ANOVA that further supports the validity of these associations, see Appendix F.

[13]Higher-order and nested association rules are reported for completeness in Appendix G and confirm the strengths of the reported associations.

spread advantage across multiple points of the curve simultaneously.

Beyond these primary attributes, we find that bonds with spreads-on-issue-date exceeding 100 basis points (confidence 0.688) and bonds with yields-on-issue-date greater than 3.2% (confidence 0.623) are associated with positive spreads. Callable bonds, while showing lower confidence (0.559), exhibit substantial support (0.350), indicating that such bonds comprise a large portion of the market with a modest positive spread tendency.

Maturity-related attributes play a critical role in positive spreads, with the term structure framework revealing distinct effects for nominal maturity versus duration. Bonds with remaining maturity above 14.4 years, maturity at issuance date above 17, duration exceeding 7 years, and less than 1.1 active years are associated with positive spreads. Although these attributes capture different pricing dimensions, in general, they reflect that green bonds with relatively longer maturities are typically associated with positive yield spreads.

The economic interpretation of these association aligns with established municipal finance principles. Federally taxable green bonds typically carry higher borrowing costs due to the absence of tax advantages, reflected in their positive spreads relative to Treasuries. The term structure methodology allows us to observe how this tax effect compounds across the entire maturity spectrum. At-par issuance signals balanced risk-return positioning that holds across different curve segments, while longer-maturity bonds naturally command term premiums that manifest as positive spreads when measured against the full Treasury structure. Longer-maturity green bonds command positive spreads because they embed extended exposure to green-specific uncertainties—including evolving certification standards, regulatory frameworks, and use-of-proceeds credibility over multi-decade horizons. When evaluated against the complete Treasury curve (rather than single maturity points), these bonds price in a term premium that compensates for both conventional duration risk and green project uncertainty, with the curve-based green bond yield spread measurement capturing how this premium manifests across the entire maturity spectrum (Karpf and Mandel, 2018; Partridge and Medda, 2018).

4.2. Attribute associations for negative green bond spreads

Table 3b reports the support, confidence, and lift metrics for negative spread attribute associations, as ranked by confidence. The term structure approach identifies low spreads-on-issue-date (less than 17 basis points) as the leading attribute, with confidence of 0.774 and support of 0.183. This indicates that 77.4% of bonds issued with narrow initial spreads continue to exhibit negative spreads when evaluated against the term structure of risk-free rates. The persistence of tight pricing from primary to secondary markets, now measured across the full curve rather than single points, provides evidence of sustained demand pressure beyond the initial issuance stage.

Additional negative spread associations include low yields-on-issue-date (below 1.7%, confidence 0.724), non-callable (confidence 0.670, support 0.251) and at-premium pricing. At-premium pricing shows the highest support (0.479) among negative attributes, indicating that this is a prevalent feature in the market, with 63.1% of premium bonds associated with negative spreads. Tax-exempt bonds and bonds with coupons between 5–8.5% exhibit similar confidence (around 62%) with support 0.492 and 0.303, respectively.

Short-maturity and low-duration attributes are strongly associated with negative spreads. Bonds with maturity below 8 years (confidence 0.706), remaining years to maturity below 4.7 years (confidence 0.706) and with duration under 2.8 years (confidence 0.596) exhibit negative spreads, but through different mechanisms. Short maturity reduces uncertainty regarding project completion and green certification maintenance, creating concentrated demand from ESG-focused investors seeking lower duration risk.

The term-structure-based screening reveals important nuances in green bond pricing patterns. Low initial spreads signal bonds that were tightly priced relative to the entire Treasury curve at issuance, and this relative pricing advantage persists over time. Rather than affecting only a certain maturity, investor demand negative spreads simultaneously across all relevant discount points. Non-callable bonds provide duration certainty across the curve, making them particularly attractive to investors managing term structure risk and contributing to spread compression. The premium issuance, another negative spread association, reflects oversubscription dynamics that influence pricing along the full curve, with investors willing to accept below-Treasury yields throughout the bond's remaining term structure. Furthermore, high-net-worth investors seeking after-tax returns evaluate these bonds against the full tax-adjusted Treasury curve, and strong demand in this segment compresses spreads across maturities. The presence of higher coupons (5–8.5%) in negative spread bonds suggests that issuers structure these bonds to attract tax-sensitive investors despite—or perhaps enabling—the tighter curve-relative pricing. Duration-based screening proves especially effective in this framework: low-duration green bonds offer protection against non-parallel yield curve movements, making them valuable during periods of monetary policy uncertainty when curve shape becomes unpredictable (Tiwari et al., 2023; Chen et al., 2021).

4.3. Stability of associations over time

Figure 3 tracks the monthly evolution of confidence, support and lift metrics for the attribute associations of the positive and negative green bond yield spreads. We find that federal taxable bonds maintain consistently high confidence in positive spreads, ranging between 0.9–1.0. This stability confirms that taxable green municipal bonds command persistent yield premiums when evaluated against the full term structure of the Treasury curve. At-par pricing similarly demonstrates high confidence in positive spreads, though with slightly more variation compared to federal taxable bonds. Other positive spread attributes, including duration-related measures, callable status, and initial spread levels, display greater temporal volatility. Support levels for most positive spread attributes remain relatively stable, though concentrated among fewer bond characteristics as the market matures. Lift metrics further show that federal taxable and at-par bonds remain the strongest associations with positive spreads over time (with values consistently above 1.5).

Negative spread associations exhibit more complex temporal dynamics. Confidence levels for attributes like low spreads-on-issue-date and non-callable show upward trends, particularly notable after 2021. Support metrics reveal that premium-issued bonds and tax-exempt bonds comprise an increasing share of the negative spread segment, reflecting the growing prevalence of these structures as investor demand for green bonds intensifies. However, lift values for negative spread attributes display more variation than their positive counterparts till 2023, suggesting that the relationship between specific bond characteristics and negative spreads becomes less deterministic potentially due to strong market demand pressures. The term structure framework captures how this demand effect manifests across multiple curve points simultaneously. Bonds with strong ESG appeal compress spreads relative to Treasuries throughout their maturity spectrum.

Although tax status and pricing strategy remain consistent associations in both tenor-based (Sehatpour et al., 2024) and term-structure screening frameworks (Sojoudi et al., 2025), the term structure approach reveals more pronounced maturity effects, with duration-related attributes featuring more frequently among top-ranked rules. The term structure approach incorporates discount rates varying with each cash flow's tenor, capturing how duration risk manifests across the entire curve (Chen et al., 2021). Duration represents a comprehensive measure of interest-rate exposure when bonds are valued against the entire Treasury curve. This feature distinguishes between bonds with similar stated maturities but different cash flow profiles, such as high-coupon versus low-coupon bonds, that exhibit markedly different sensitivities to curve reshaping and term premium dynamics. This distinction is critical for duration-neutral portfolio construction and liability-driven strategies seeking both ESG alignment and stable relative value in diverse interest-rate scenarios (Fleckenstein and Longstaff, 2020; Bai et al., 2021). We next offer an empirical demonstration of green bond portfolio construction based on the term structure screening that carries such benefits.

5. Green bond portfolios based on term-structure informed screening

The ARL-identified structural attributes can provide a systematic foundation for translating spread analytics into actionable sustainable portfolio strategies. Next, we propose a green bond portfolio construction framework to identify high performance attribute-defined portfolios to demonstrate the economic significance of the proposed ARL screening of green bond yield spreads carrying information from their term structure.

The main objective of the application is to examine how the structural attributes identified through the ARL screening, attributes such as tax status, maturity, duration, callability, and coupon rates, can be integrated into a practical bond ladder strategy. The novelty of our approach lies in its combination of three key elements: the green bond yield spread embedding information from the term structure, the rule-mining procedure identifying structural attributes associated with positive spreads, and a dynamic investment mechanism governed by duration constraints. From an investor's perspective, positive spreads (meaning a yield above Treasury rates) may reflect market inefficiencies, illiquidity premiums, or structural features, such as tax status, that create clientele segmentation rather than purely compensating for higher risk.[14] The screening framework thus identifies bonds positioned to capture value from structural mispricing and secular demand trends, with credit risk playing a secondary role given the historically low default rates[15] in municipal markets. This three-element approach enables investors to construct portfolios that maintain stable duration exposure, preserve downside protection, and exhibit smooth cumulative returns relative to traditional Treasury ladders. The framework thus provides a practical and replicable foundation for the integration of environmental instruments into mainstream fixed-income investment strategies.

5.1. Green bond portfolio construction

We consider four sustainable bond ladder portfolio designs: (i) homogeneous portfolios constructed from ARL-screened groups, (ii) hybrid portfolios blending screened green bonds with Treasury securities, (iii) duration-targeted portfolios constructed from the (same) ARL-screened groups maintaining stable interest-rate exposure, and (iv) hybrid duration-targeted portfolios. The construction of homogeneous portfolios captures the value of structural screening, while hybrid portfolios balance green allocation and liquidity. The duration based portfolios are tailored to manage interest-rate risk, while hybrid duration based portfolios integrate interest risk with green allocation and liquidity.

The portfolio application proceeds within a discrete-time investment framework in which purchases occur at regular semiannual intervals. These synthetic instruments are not traded in the market but are calibrated to reproduce the cash-flow and valuation behaviour of the corresponding green bonds based on their term-structure yields.[16] This design ensures that

[14]As ESG-driven demand intensifies, these spreads tend to compress, enabling holders to benefit from both yield carry and price appreciation. This mechanism is evident in the post-2022 regime shift toward persistently negative spreads (Figure 2a and Table 2), where earlier-identified positive-spread bonds benefited from the persistent positive financial performance identified through the screening lens. Additionally, tax considerations create distinct investor clienteles: federally taxable bonds primarily attract international investors seeking higher nominal yields, while tax-exempt structures appeal to domestic high-net-worth investors prioritizing after-tax returns (Sehatpour et al., 2024).

[15]Credit ratings are more central to corporate bonds, where higher default risk makes them a key pricing factor, whereas municipal bonds are typically backed by state and local governments and exhibit very low default rates, reducing the reliance on ratings (Wang, 2022).

[16]This synthetic approach is a deliberate methodological choice that isolates the effects of term-structure pricing and structural screening from transaction-level noise, enabling clearer identification of the fundamental relationships between bond attributes and performance. The framework provides a clean test of whether term-structure-based screening generates economically meaningful portfolio differentiation. Real-world im-

the portfolio valuation depends solely on the term-structure information and not on market pricing noise or liquidity effects.

5.1.1. Homogeneous bond ladder portfolios

Let purchases occur every $\Delta = \frac{1}{2}$ years at dates $d_k = k\Delta$ ($k = 0, 1, 2, \ldots$). At each d_k, a fixed fraction α of the initial wealth W_0 is allocated to *one* new green bond with tenor T from the purchasing groups filtered by ARL rules. The remaining wealth is held in a money-market account accruing the daily risk-free rate r_n. Trading days are indexed by $t = 0, 1, 2, \ldots$ with day-count step δ, t_k denotes the day corresponding to d_k, and r_n is the daily risk-free rate.

The green bond purchased at d_k is converted to a synthetic zero coupon bond with face value FV_k^G and corresponding green zero coupon yield $YTM_{k,n}^{(GZCB)}$ calculated in equation 1 using the rates extracted from the fitted yield curves according to the partitions we described in Table 1. Then the green bond price of day-n is given by:

$$P_{k,t}^G = \frac{FV_k^G}{\left(1 + YTM_{k,t}^{(GZCB)}\right)^{\tau_{k,t}}}, \qquad \tau_{k,t} = \max\big\{\, T - \delta(t - t_k),\, 0 \,\big\}, \tag{4}$$

where $\tau_k(n)$ represents the remaining time to maturity at day t. The number of bond units acquired at the purchase date is:

$$q_k^G = \frac{\alpha W_0}{P_{k,t_k}^G} = \frac{\alpha W_0}{FV_k^G} \left(1 + YTM_{k,t_k}^{(GZCB)}\right)^T. \tag{5}$$

Let M_n denote the cash (money-market) account. It compounds daily and decreases by αW_0 on days of purchase:

$$M_{t+1} = \left(M_t - \alpha W_0\, \mathbf{1}_{\{t = t_k\}}\right)(1 + r_k), \qquad M_0 = W_0, \tag{6}$$

where $\mathbf{1}_{\{\cdot\}}$ is an indicator function identifying portfolio rebalancing (purchase) dates, taking value one when a new bond is purchased and zero otherwise. The daily updated portfolio value is computed as:

$$V_t^G = M_t + \sum_{k:\, t \geq t_k} q_k^G\, P_{k,t}^G. \tag{7}$$

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plementation would introduce transaction costs and liquidity constraints that moderate absolute returns, but these frictions do not alter the core finding that structurally screened portfolios exhibit superior risk-adjusted performance relative to duration-matched benchmarks, as this advantage stems from curve-level pricing dynamics rather than trading execution.

This specification ensures that the portfolio tracks the *model-implied performance* of the green term structure itself rather than historical traded bond prices. Consequently, the results reflect theoretical yield-curve dynamics and structural rules identified by the ARL screening, providing an internally consistent test of how those structural characteristics influence portfolio behaviour.

To construct the Treasury benchmark, we follow the same tenor-specific valuation structure used for the green bonds, but we replace the green zero-coupon yields with the bootstrapped U.S. Treasury zero rates and remove the coupon component, since the synthetic benchmark is priced as a pure discount bond. Let $r_t^{(Tr)}(\tau)$ denote the Treasury zero rate at maturity τ on day t.[17] Thus, the price $P_{k,t}^{Tr}$ of the k-th benchmark Treasury benchmark bond on day t with face value FV_k^{Tr} and maturity T is expressed as:

$$P_{k,t}^{Tr} \;=\; \frac{FV_k^{Tr}}{\left(1 + r_{k,t}^{(Tr)}\right)^{\tau_{k,t}}}, \qquad \tau_{k,t} \;=\; \max\Big\{\, T - \delta(t - t_k),\, 0 \,\Big\}. \tag{8}$$

The total value of the Treasury benchmark portfolio combines its money-market allocation with the values of the benchmark Treasury components:

$$V_t^{Tr} = M_t + \sum_{k:\, t \geq t_k} q_k^{Tr}\, P_{k,t}^{Tr}, \tag{9}$$

where M_t is the accumulated cash (rolled forward at the daily risk-free rate), and q_k^{Tr} represents the number of purchased Treasury bonds. The proposed bond allocation produces a homogeneous bond ladder that considers bonds of fixed maturity across the ARL-screened groups. Each semiannual purchase adds one synthetic bond from a specific ARL-screened group, allowing comparison of distinct structural rules. This setup enables a controlled assessment of how association-based structural differences translate into cumulative portfolio dynamics.

[17] Bootstrap procedure: Treasury zero rates are obtained from the par yield curve by recursively solving

$$1 = \sum_{n=1}^{\tau-1} \frac{c}{(1 + r_t(n))^n} + \frac{1 + c}{(1 + r_t(\tau))^{\tau}}, \qquad c = y_t(\tau),$$

starting from the shortest maturity and iterating upward. The resulting discount factors are $DF_t(\tau) = (1 + r_t(\tau))^{-\tau}$.

5.1.2. Duration-targeted portfolio

In the duration-targeted application, the investment rule is extended to include a portfolio duration constraint. The duration of the portfolio at any time t is:

$$D_p(t) = \sum_i w_i D_i(t), \tag{10}$$

where $D_i(t)$ is the Macaulay duration of bond i and w_i represents its portfolio weight. At each investment date, bonds are selected such that the overall duration remains within a target interval $[D_L, D_U]$. The selection criterion follows a cost-minimization condition, which ensures that the chosen bonds achieve the target duration range at the lowest aggregate price. This dynamic allocation approach creates an inhomogeneous bond ladder in which maturities differ between rungs, but the overall duration of the portfolio remains stable over time.

This strategy reflects institutional investment mandates that require duration alignment with long-term liabilities (e.g., pension obligations and insurance claims) while allowing flexibility in security selection. By construction, this approach facilitates a direct comparison between green and Treasury portfolios with equivalent interest-rate exposure, isolating the role of structural attributes and term-structure-based pricing in shaping portfolio outcomes.

5.1.3. Hybrid (homogeneous and duration-targeted) portfolios

To analyze portfolio designs that balance sustainability exposure and liquidity, we construct hybrid portfolios that blend screened green bond portfolios with the Treasury benchmark. For each screened group G and at each trading day t, the hybrid portfolio holds a fixed fraction $\lambda \in \{1.00, 0.75, 0.50, 0.25\}$ of wealth in the group G_n green portfolio and the remaining $(1 - \lambda)$ in the tenor- and duration-matched Treasury ladder. Denoting by V_t^G the value of the screened green portfolio for group G and by V_t^{Tr} the value of the Treasury benchmark on day t, the hybrid portfolio value $V_t^{H_n}$ is evaluated as:

$$V_t^{H_n}(\lambda) = \lambda\, V_t^{G_n} + (1 - \lambda)\, V_t^{Tr}. \tag{11}$$

This specification preserves the underlying term-structure and duration properties of both legs while allowing the green allocation λ to be varied systematically to study the trade-off between risk–return performance and liquidity. This hybrid construction is applied to both the homogeneous tenor-based portfolios and the duration-targeted portfolios.

This design reflects a practical constraint faced by large institutional investors: while screened green bonds exhibit favourable performance characteristics, their secondary-market liquidity remains limited relative to Treasury securities (Febi et al., 2018; Environmental Finance, 2023). Thus, hybrid portfolios allow investors to retain exposure to green bonds, while incorporating liquid government securities to support portfolio scalability.

5.1.4. Implementation procedure and assumptions

The analysis assumes that all green bonds are represented by their synthetic zero-coupon equivalents derived from bootstrapped yield curves, ensuring consistency in pricing and comparability across time.[18] Each purchase invests an equal fraction ($\alpha = 10\%$) of the initial wealth ($W_0 = 1M(USD)$), implying constant proportional allocation across investment dates. The reinvestment frequency is semiannual, while valuation and compounding occur daily based on the risk-free rate. A nominal annual risk-free rate (r_f) of 1% is assumed, consistent with long-term neutral conditions and the guidance to avoid distortions from the short-term monetary policy cycle.[19] Transaction costs and bid–ask spreads are neglected as simplifying assumptions in our theoretical framework. This allows focusing on structural spread and duration effects. The benchmark portfolio is constructed from U.S. Treasury zero-coupon bonds with equivalent maturities, allowing direct comparison of performance, stability, and risk-adjusted metrics.

For the green bond portfolio analysis, we consider four screened green bond groups, from G1 to G4, based on the highest-ranked first-order ARL rules that associated with positive green bond yield spreads (see Panel A of Table 3). These rules isolate the strongest individual attributes associated with financially and sustainably attractive green bonds. Moving down the rule ranking, we select rules that generate distinct, non-overlapping bond subsets and provide variation in structuring attributes, primarily across tax status and coupon range. Note also that callable bonds are excluded from the portfolio construction since their embedded call option exposes investors to reinvestment risk and uncertain cash-flow timing.

[18]Our portfolio analysis uses in-sample fitted curves. True out-of-sample validation (e.g., fitting on 2020-2023, testing on 2024) is left for future work.

[19]Results are qualitatively robust to alternative risk-free rate assumptions. Using actual short-term rates affects absolute returns but preserves relative portfolio rankings.

Consistent with this screening approach, G1 includes bonds with *federally taxable and state tax-exempt* bonds, G2 consists *spread-at-issuance higher than 100 bps*; G3 contains bonds with *remaining years-to-maturity above 14.4 years*; and G4 contains bonds with *duration greater than 7 years.*[20]

For the pricing process, see equations (1) and (4), we would need to define the characteristics of the bonds used in the portfolios, specifically their tax status, callability, and coupon range, so that the synthetic instruments align with the yield partitions reported in Table 1. At each purchasing date, we assume a synthetic bond whose tax status reflects the dominant tax category[21] within the group and whose coupon rate equals the median coupon of the purchasing group. As only non-callable bonds are considered, these synthetic instruments can be consistently assigned to one of the nine yield partitions in Table 1 for yield extraction.[22]

Table 4 summarizes the purchasing-bond characteristics and the corresponding curve partitions used for constructing the screened portfolios. For each purchasing group, we assign a synthetic bond whose characteristics reflect the representative attributes identified by the screening rules. This leads to four purchasing-bond groups, each aligned with a specific curve groups ($P1 - P9$) defined in Table 1. For example, for G_1 taxable bonds, the median coupon is 2.5%, thus the underlying purchasing bonds are non-callable, carry a 2.5% coupon, and are federally taxable and state tax-exempt, corresponding to curve partition P_1. For G_2 bonds having spread at issuance higher than 100bps, the median coupon is 3.5%, thus the synthetic purchasing bonds are non-callable 3.5% coupon bonds which are federally taxable and state tax-exempt, which associates with curve partition P_2. For bonds with remaining years-to-maturity above 14.4 years, namely G_3, the median coupon is 5.5%, thus

[20]Several rules from Panel A of Table 3 are excluded from the portfolio construction to avoid bond overlap and maintain distinct screening criteria. Specifically, we exclude: at-par pricing (Rule 2), yield-on-issue-date higher than 3.2 (Rule 5), maturity-on-issue-date higher than 17 (Rule 6), active years less than 1.1 (Rule 8), spread-on-issue 57-100 (Rule 9), and callable bonds (Rule 10).

[21]The tax status of each synthetic bond is determined by selecting the most frequently occurring tax status among bonds within the corresponding purchasing group, ensuring that the synthetic instrument reflects the dominant tax characteristic of the screened population.

[22]In practice, it is unrealistic to expect a real green bond to match every desired combination of attributes and maturities at each purchasing date. To address this challenge, we adopt a synthetic bond approach that allows us to simulate bond performance using the observed yield curves.

the representative synthetic purchasing bonds are non-callable bonds with a 5.5% coupon that are federally taxable, mapped to curve partition P_4.[23] Finally, G_4 (bonds with duration greater than 7 years have median coupon of 4%) includes non-callable bonds with a 4% coupon that are federally and state tax-exempt, corresponding to curve partition P_3.

For the homogeneous portfolios, the synthetic bonds are issued at a fixed tenor of $T = 10$ years at each purchasing date. For the duration-based approach, the bond chosen at each purchasing date is selected such that it brings the overall portfolio duration back to 10 years (see equation 10).[24] To maintain a realistic implementation, we allow a tolerance band of ± 1 year around the target duration, so the acceptable duration interval is $[D_L, D_U] = [9, 10]$ years. A more comprehensive description of the assumptions of the portfolio composition and allocation dynamics is provided in Appendix H.

5.2. Green bond portfolios performance

Portfolio performance is evaluated using standard fixed-income measures such as the Sharpe ratio, Sortino ratio, and maximum drawdown.[25] These indicators, together with cumulative and annualized returns, provide a comprehensive assessment of both performance and resilience of the green bond portfolios relative to Treasury benchmarks.

We next document the performance of the four types of sustainable bond portfolios formulated based on ARL-screened portfolios, namely, homogeneous, hybrid homogeneous, duration-targeted and hybrid duration-targeted portfolios.

[23] In Group 3, the screening rule selects green bonds with remaining maturities greater than 14.4 years. Since our analysis considers only non-callable bonds, and this group naturally includes many callable securities that are typically issued with longer maturities and, consequently, longer durations, we retain this group because it captures a unique set of structuring characteristics that would otherwise be excluded.

[24] For the duration-based portfolios, when a real bond satisfying the duration constraint cannot be found, we again assume a 10-year tenor for the synthetic purchasing bond for simplicity. Keeping this group provides valuable insight into how synthetic bonds with these structural features behave in portfolio settings and offers useful guidance for issuers seeking more effective structuring design.

[25] Daily portfolio returns are calculated as $R_t = (V_t - V_{t-1})/V_{t-1}$, and cumulative returns as $CR_N = \prod_{t=1}^{N}(1 + R_t) - 1$. The Sharpe ratio is defined as Sharpe $= E[R_n - r_f]/\sigma(R_n)$, where R_n is the portfolio return, r_f the risk-free rate, and $\sigma(R_n)$ the return volatility. The Sortino ratio replaces $\sigma(R_n)$ with the downside deviation $\sigma_d(R_n)$ to focus on negative return variability. The maximum drawdown is MDD $= \max_{n\in[0,N]}\big(\max_{s\leq n} V_s - V_n\big)/\max_{s\leq n} V_s$, capturing the largest peak-to-trough decline in portfolio value.

5.2.1. *Homogeneous portfolio performance: The value of structural screening*

Table 5 compares the performance of the four screened green bond portfolios (G_1 − G_4) with a maturity-matched Treasury ladder benchmark at 10 years. During 2020–2024, all screened green portfolios generated positive cumulative returns, whereas the Treasury benchmark suffered a substantial loss of –4.90%. Specifically, G_4 (non-callable bonds with a 4% coupon and federally/state tax-exempt) deliveres the highest overall return of 2.60%, followed closely by G_3 (non-callable bonds with a 5.5% coupon and federally taxable) and G_1 (non-callable bonds with a 2.5% coupon and federally taxable/state tax exempt). G_2 (non-callable bonds with a 3.5% coupon and federally taxable/state tax exempt) posts a more modest 1.28% return.

The superior performance of screened green portfolios is particularly evident in risk-adjusted metrics and downside protection. Maximum drawdowns for the green groups ranged from –1.04% (G_1) to –1.54% (G_2), dramatically lower than the Treasury benchmark's –10.36%. This finding is consistent with Baker et al. (2022) and Bhanot et al. (2022), who document strong and persistent investor demand for green bonds, including municipal issues, driven by ESG preferences and stable ownership structures, which can contribute to more resilient pricing behavior. However, our results extend these findings by demonstrating that structurally screened green bond portfolios, constructed using term-structure-based spreads and ARL-identified attributes, exhibit materially improved downside protection at the portfolio level.

Figure 4 depicts the cumulative return paths for the screened portfolios and illustrates the divergence in cumulative return paths. The Treasury portfolio experiences severe drawdowns during 2022-2023, coinciding with the Federal Reserve's aggressive monetary tightening cycle. However, all green portfolios maintain relatively stable trajectories, with cumulative returns fluctuating within a narrower band. This stability reflects the combined effect of (i) coupon income and curve-relative pricing advantages embedded in term-structure-based spreads used for portfolio construction, and (ii) persistent demand from institutional investors with explicit sustainability mandates, which provides a natural stabilization mechanism during periods of market stress (Fatica and Panzica, 2024). In line with Silva et al. (2024), which show that green bond portfolios exhibit comparatively stronger performance and more favorable risk–return characteristics during periods of elevated uncertainty and stress, we demonstrate their defensive role when climate-related risks intensify.

Year-by-year performance, reported in Table 5, reveals the structural resilience of screened green portfolios across distinct monetary policy regimes. During 2020–2021, all green groups generate positive returns, with G_1, G_3, and G_4 outperforming the Treasury benchmark by approximately 1.5–2.0 % annually (Figure 4). This period of accommodative monetary policy favours fixed-income securities broadly, while performance differences between groups reflect structural attributes such as coupon levels, call protection, and term-structure positioning, which support income stability and favourable curve-relative pricing. The 2022 Federal Reserve tightening cycle marks a critical inflection point: while the Treasury benchmark declined sharply (–8.2%), green portfolios recorded substantially smaller losses, ranging from –0.5% (G_4) to –1.2% (G_2). Group characterised by higher coupons and tax-exempt structures exhibit the strongest downside protection, whereas portfolios defined by taxable bonds experience relatively larger drawdowns, consistent with differences in term-structure positioning and curve-relative pricing during the rate-hiking cycle.

During the subsequent recovery phase, Treasury returns rebounded more rapidly from their trough, reflecting the larger initial drawdown. By contrast, green portfolios exhibit a slower recovery rate, with G_3 being the only screened portfolio to deliver a positive return in 2024. This slower recovery of green portfolios is consistent with the tightening of green bond yield spreads observed during the post-2022 period (Figure 2a and Table 2), which reflects heightened demand pressure and increasingly negative curve-based spreads. As new green bonds are added to portfolios at relatively higher prices during this phase, the scope for price-based rebound was mechanically reduced, dampening short-term recovery speed. Nevertheless, these temporal patterns underscore that structurally screened green bonds provide superior downside protection while maintaining stable performance dynamics through periods of interest-rate stress.[26]

[26] The 2020–2024 sample period coincides with an unprecedented macroeconomic environment characterized by pandemic-related disruptions, fiscal stimulus, and rapid monetary policy shifts. While this period provides a demanding stress-test for portfolio strategies, it may not be representative of long-run market dynamics. For future research and once sufficient data become available, extending the analysis to longer sample periods would strengthen the validity of the findings.

Figure 5 offers distributional evidence on the performance of homogeneous screened portfolios. Beyond differences in cumulative outcomes, the figure highlights substantial variation in return dispersion between groups, with G_3 and G_4 exhibiting more compact return distributions and fewer extreme negative observations, while G_2 displays greater downside dispersion during periods of heightened volatility. These patterns indicate that structural screening affects not only average performance, but also the shape of return distributions.

Figure 6 shows risk–return scatter plots for screened portfolios and the Treasury benchmark (per year and during the sample period) providing further cross-sectional evidence on the risk–return characteristics of homogeneous screened portfolios. We find that the green portfolios cluster at lower levels of annualized volatility than the Treasury benchmark, while achieving comparable or higher total returns. The Treasury portfolio, by contrast, is consistently positioned at higher volatility and, particularly during 2022–2024, at substantially lower return levels. The Sharpe-scaled plots further indicate that the screened green portfolios deliver more favourable risk-adjusted outcomes across most years, even when absolute returns are muted. This pattern is especially pronounced in stressed periods, where green portfolios maintain tighter risk–return trade-offs relative to the Treasury benchmark.

In summary, beyond achieving higher raw returns, structurally screened green portfolios offer improved risk-adjusted positioning and capital efficiency. Tighter and increasingly negative curve-based green bond spreads in the post-2022 period (see Figure 2a and Table 2) raise entry prices for newly added green bonds, mechanically moderating recovery speed while reinforcing downside protection. In other words, term-structure-based screening shapes cumulative performance, return dispersion and drawdown behaviour, especially under stressed interest-rate conditions.

5.2.2. Hybrid portfolios: Balancing green allocation and liquidity

Table 6 reports the performance of hybrid portfolios that combine ARL-screened green bonds with Treasury securities at four allocation levels: 100%, 75%, 50%, and 25% green weight with a clear and monotonic pattern becoming apparent. As the green allocation declines, overall returns converge toward the Treasury benchmark, while maximum drawdowns increase. For example, G_1 hybrid portfolios deliver cumulative returns of 2.35% at 100% green, 0.54% at 75%, –1.28% at 50%, and –3.09% at 25%, with drawdowns rising correspondingly as green exposure is reduced. Green bonds provide consistent downside protection (within the sample period), where even partial green allocations meaningfully reduce portfolio tail risk relative to Treasury-dominated portfolios. Additional summary evidence for these allocation effects is reported in Figures 8 and 9.

Further, across most groups, the 75% green portfolios outperform the corresponding 50% hybrids in total return and risk-adjusted terms. For instance, G_3 with a 75% green allocation achieves a positive cumulative return and a higher Sharpe ratio compared to the 50% hybrid portfolio, while also maintaining substantially lower drawdown exposure. Thus, a 75% green allocation represents an effective balance between retaining exposure to screened green bonds and moderating overall portfolio risk.

Figure 7 illustrates the cumulative return paths of the hybrid portfolios. Portfolios with higher green weights exhibit smoother return trajectories and smaller fluctuations through the 2022–2023 tightening cycle, whereas Treasury-heavy allocations experience more pronounced volatility. This pattern reinforces that the benefits of hybrid portfolios arise from the interaction between screened green bond exposure and Treasury holdings, rather than from mechanical shifts in risk-free allocation alone.

From a portfolio construction perspective, these findings have three implications. First, they support the role of screened green bonds as a key component of fixed-income allocations - compared to a marginal ESG overlay. Second, they demonstrate that meaningful green exposure can be achieved without sacrificing diversification or liquidity. Third, they highlight the importance of selective allocation: indiscriminate investment across all green issuances would likely dilute performance, whereas portfolios constructed using term-structure-based spreads and ARL-identified attributes preserve both downside protection and stable performance dynamics.

5.2.3. Duration-targeted portfolios: Managing interest-rate risk

Figure 10a shows the cumulative return paths of the duration-targeted screened green bond portfolios relative to the Treasury benchmark. Table 7 reports the performance of duration-targeted portfolios that maintain between 9- and 11-year duration range through dynamic bond selection at each semiannual rebalancing date. Overall, duration-targeted green portfolios generate cumulative returns ranging from 0.53% (G_2) to 8.68% (G_3), while the duration-matched Treasury portfolio recorded a loss of –10.02%. G_3 delivered the strongest performance, with an 8.68% cumulative return, a Sharpe ratio of 0.17, and a maximum drawdown of –4.28%. Although the Sharpe ratio remains modest in absolute terms, it is the only positive value among the duration-targeted portfolios, indicating superior risk-adjusted performance relative to both other green groups and the Treasury benchmark. The Treasury portfolio, by contrast, exhibited a Sharpe ratio of –0.51 and a maximum drawdown of –14.94%. G_1 and G_4 also outperformed the Treasury portfolio, delivering cumulative returns of 2.60% and 3.28%, respectively, with maximum drawdowns of –1.88% and –2.18%. G_2 achieved a smaller but still positive return of 0.53%, while avoiding the severe losses observed for Treasuries. As shown in Figure 10b, all portfolios maintained comparable duration exposure throughout the sample period, confirming that the observed return differentials are not attributable to duration mismatches or mechanical differences in interest-rate sensitivity.

Year-by-year performance patterns further highlight the resilience of duration-targeted green portfolios across monetary policy regimes (Figure 10a). During the 2020–2021 period of accommodative policy, G_3 generated annual returns exceeding 3.5%, outperforming the Treasury benchmark by approximately 4–5 % per year. The sharpest divergence emerges in 2022, when aggressive Federal Reserve tightening leads the duration-matched Treasury portfolio to decline by –12.8%, while G_3 records a comparatively modest loss of –1.2%. In the subsequent 2023–2024 period, G_3 returns to a positive annual performance, while the Treasury portfolio exhibits only partial recovery. The cumulative return dynamics underlying these patterns is summarized in Figure 11, while Figure 12 provides complementary evidence on the dispersion and risk–return positioning of duration-targeted portfolios. We conclude that the performance advantage of G_3 emerges early and persists through periods of elevated interest-rate volatility.

The cross-sectional variation across the green groups further clarifies the sources of performance. G_1, composed of low-coupon federally taxable bonds, delivered lower returns (2.60%) and a negative Sharpe ratio (–0.08), reflecting weaker income support. G_2, consisting of mid-coupon taxable bonds, recorded the weakest green performance (0.53%, Sharpe –0.13), suggesting limited benefits in the absence of compensating structural features. G_4, comprising higher-coupon tax-exempt bonds, achieved stronger returns (3.28%) and a Sharpe ratio of –0.06, positioning it as a viable alternative for investors prioritising current income over total return. In contrast, G_3 combines tax-exempt status with favourable term-structure positioning, resulting in the most robust performance in both absolute and risk-adjusted measures.

A comparison between duration-targeted and homogeneous portfolio strategies, examined in Section 5.2.2, shows that while homogeneous portfolios generated cumulative returns of 1.28% to 2.60% with relatively shallow maximum drawdowns (–1.04% to –1.54%), duration-targeted portfolios achieved higher returns (0.53% to 8.68%) at the cost of moderately larger drawdowns (–1.88% to –4.28%). These differences reflect the fundamental contrast between tenor-based and duration-based approaches: tenor matching prioritises stability and capital preservation, whereas duration targeting accepts greater variability in exchange for enhanced return potential through dynamic exposure to the term structure. The superior performance of duration-targeted G_3 relative to the best-performing homogeneous portfolio also underscores that investors with longer horizons and tolerance for moderate drawdowns can benefit from duration-based strategies, while more risk-averse institutions may prefer tenor-matched allocations.[27] Furthermore, this substantial outperformance demonstrates how term-structure-based screening captures value beyond interest-rate positioning. Since duration is equalized by construction, other mechanisms may drive the differential. Screened green bonds entered portfolios with positive term-structure spreads, generating higher yield carry than duration-equivalent Treasuries. The secular compression of spreads from positive (2020-2021) to persistently negative (2022-2024) also produces capital gains for existing holdings as green bond prices appreciated relative to Treasuries. Finally, the non-callable structure of screened bonds provides positive convexity, enhancing returns during periods of rate volatility. Such effects illustrate that the screening framework can identify bonds positioned to benefit from both structural pricing advantages and favorable market dynamics,

[27] Green municipal bond markets are at least as illiquid, and in many cases more illiquid, than conventional municipal bond markets, reflecting both general municipal market frictions and the relative immaturity of the green segment (Febi et al., 2018; Karpf and Mandel, 2018). Under the conservative assumption of a round-trip transaction costs of 50 basis points, which exceeds the upper end of documented effective spreads and dealer mark-ups in U.S. municipal bond markets (Wu, 2018; Wu et al., 2025; Griffin et al., 2025), semi-annual rebalancing reduces cumulative returns (by approximately 5%) with the performance advantages remaining economically meaningful within our sample.

rather than merely capturing duration exposure.

5.2.4. Hybrid duration-targeted portfolios: Balancing green allocation and liquidity while managing interest risk

Table 8 reports the performance of duration-targeted hybrid portfolios that combine screened green bonds with Treasury securities at green allocation levels of 100%, 75%, 50%, and 25%. The results indicate that even partial green allocation within a duration-matching framework delivers meaningful improvements in risk–return performance relative to Treasury-only portfolios. For G_3, the 75% green hybrid achieves a cumulative return of 5.82%, a Sharpe ratio of 0.09, and a maximum drawdown of –6.15%, compared to a –10.02% return and –14.94% drawdown for the duration-matched Treasury portfolio. A green weight of 50% still yields a positive cumulative return of 2.96% with a drawdown of –8.09%, confirming a monotonic relationship between green allocation and downside protection that mirrors the pattern observed in tenor-based hybrid analysis. Notably, hybrid Group 3 maintains positive Sharpe ratios at both 100% and 75% green allocations (0.17 and 0.09, respectively), making them the only portfolios to achieve positive risk-adjusted performance across all duration-targeted strategies. Additional allocation-level comparisons and cross-sectional performance summaries for hybrid duration-targeted portfolios, see Figures 15 and 14.

These results extend the evidence from both homogeneous and duration-targeted portfolios, demonstrating that the stabilizing properties of structurally screened green bonds persist within duration-matched hybrid frameworks. Thus, investors can calibrate green allocations to balance return objectives, downside risk, and liquidity considerations without sacrificing duration requirements.

6. Conclusion

This study introduces a novel term structure framework for green bond valuation and portfolio construction. Unlike conventional approaches that rely on single-point tenor matching, our method embeds information from the entire yield curve by comparing bootstrapped green bond curves with Treasury curves on a daily basis. This curve-to-curve comparison captures how green bonds price across multiple maturities simultaneously, revealing dynamics that single-tenor methods cannot detect, particularly for bonds with embedded options or complex cash flow structures. Applied to Californian municipal green bonds, the term-structure-based green bond yield spreads transitioned from predominantly positive to negative after 2022. Furthermore, we use ARL to identify structural attributes associated with curve-based green bond yield spreads with the purpose of guiding the formation of dynamic ladders for the construction of green bond portfolios. We construct and evaluate the performance of ARL-screened green bond portfolios that can balance green allocation and liquidity (hybrid portfolios) and manage interest rate risks (duration-targeted portfolios).

We demonstrate that such green bond portfolios, that embed term structure information and associated to positive green bond spreads, enable superior green bond investment strategies. Screened green bond portfolios generate positive returns (1.28%-8.68%) while Treasury benchmarks lost 4.90%-10.02%, with substantially lower drawdowns. Duration-targeted strategies utilising the full curve dynamics amplify further returns while maintaining stable interest rate exposure. Hybrid allocations (50–75% green) balance sustainability objectives with risk management. Consistent with this trade-off, a 75% green allocation exhibits superior risk-adjusted performance relative to fully green and pure Treasury strategies in most groups, while the 25% Treasury allocation continues to provide meaningful liquidity support. This term structure framework provides investors and issuers with a systematic approach to green bond valuation that captures market-wide pricing information, enabling more robust portfolio construction and supporting the integration of green bonds into mainstream fixed-income markets.

6.1. Financial implications for green bonds portfolios

This study offers empirical evidence to support the fundamentally important role of structural screening in the performance of the green portfolios, compared to generic green labeling. The variation in performance between the ARL-identified groups demonstrates that green bonds do not constitute a uniform asset class. Bonds selected based on favorable term-structure spreads, specific tax status, and maturity profiles (as identified through ARL) consistently outperformed Treasury benchmarks. In contrast to studies that aggregate green bonds into a single category (Silva et al., 2024; Abuzayed and Al-Fayoumi, 2023), selection based on term-structure-based green bond yield spreads and attributes such as callability, coupon range, and tax status can materially enhance portfolio performance.

Notably, green bonds provide meaningful downside protection during periods of interest-rate volatility. Across all portfolio designs, maximum drawdowns for screened green portfolios are substantially lower than those of the Treasury benchmark, often by a factor of five to ten. This resilience reflects the combined influence of structural bond characteristics and demand stability from sustainability-focused investors. The latter effect, documented by Flammer (2021) and Fatica and Panzica (2021, 2024), indicates that green bonds benefit from a dedicated investor base that is less sensitive to short-term interest-rate fluctuations. However, structurally screened green portfolios exhibit even stronger downside resilience, reflecting the fact that the screening process concentrates exposure in bonds with more stable pricing characteristics and more predictable cash-flow profiles.

The outperformance of homogeneous portfolios constructed from structurally screened green bond groups highlights the economic value of screening for investors relative to generic green classification. Investors can obtain materially different portfolio outcomes by allocating to structurally distinct segments of the green bond market, even when all bonds carry a green label, reflecting that performance differences linked to structural attributes rather than issuer labels alone. Duration-targeted green bond portfolio strategies further isolate structural value. The strong performance of duration-matched green portfolios demonstrates that green bonds can generate outperformance even after controlling for interest-rate sensitivity. Investors operating under explicit duration mandates, such as pension funds or insurance companies, can therefore integrate screened green bonds without compromising liability-matching objectives.

Hybrid strategies facilitate effective risk management while preserving sustainability objectives, implying that ESG alignment and portfolio performance need not be mutually exclusive. Although fully green portfolios (100% allocation) achieve strong returns and low drawdowns, they may entail greater concentration risk and reduced liquidity. Hybrid green bond strategies preserve most downside protection benefits while retaining access to deep Treasury markets for rebalancing and risk management, delivering particularly attractive risk–return trade-offs. This has important implications for institutional investors operating under liquidity constraints or regulatory oversight: green bonds can function as a core fixed-income allocation, not only a peripheral ESG satellite strategy.

Moreover, we conclude that diversification is more effectively achieved across ARL-identified structural attribute groups than through conventional diversification based solely on issuer sectors or credit ratings. While traditional approaches emphasize issuer type or industry (e.g., Water, Power, Transportation), diversification across structurally screened groups captures heterogeneity in pricing behaviour and risk-return profiles that persists even within the green bond universe, leading to more pronounced performance differentiation.

For issuers, the role of bond design and market positioning is critical. Tax-exempt structures and non-callable features are associated with stronger investor demand, and bonds incorporating these characteristics consistently attract greater interest and exhibit lower yield spreads. Issuers aiming to reduce borrowing costs can benefit from incorporating these structural features when designing green bond offerings. Coupon rates and pricing strategies also influence secondary-market performance: bonds issued at par with moderate coupons tend to exhibit more stable performance, whereas low-coupon bonds display higher price volatility. Thus, careful calibration of coupon levels to prevailing market conditions and investor preferences is an important consideration in green bond issuance.

Although empirical research reports mixed evidence on whether green bonds trade at a premium or discount (Larcker and Watts (2020) and Cheng et al. (2024)), our analysis extends beyond the measurement of generic greeniums to the identification of green bonds with robust pricing dynamics. Portfolios constructed using term-structure spread analysis and ARL-based structural screening deliver both environmental benefits and superior financial performance, highlighting the value of curve-level information and data-driven attribute selection in green bond portfolio design. Moving beyond binary green classification, this framework offers a systematic way to identify segments of the green bond market with attractive risk-return profiles, supporting the joint pursuit of sustainability and financial performance.

Declaration of generative AI and AI-assisted technologies in the writing process: While preparing this work, the authors used ChatGPT to improve the manuscript's readability and language. After that, the authors thoroughly reviewed and edited the content, taking full responsibility for the manuscript's content.

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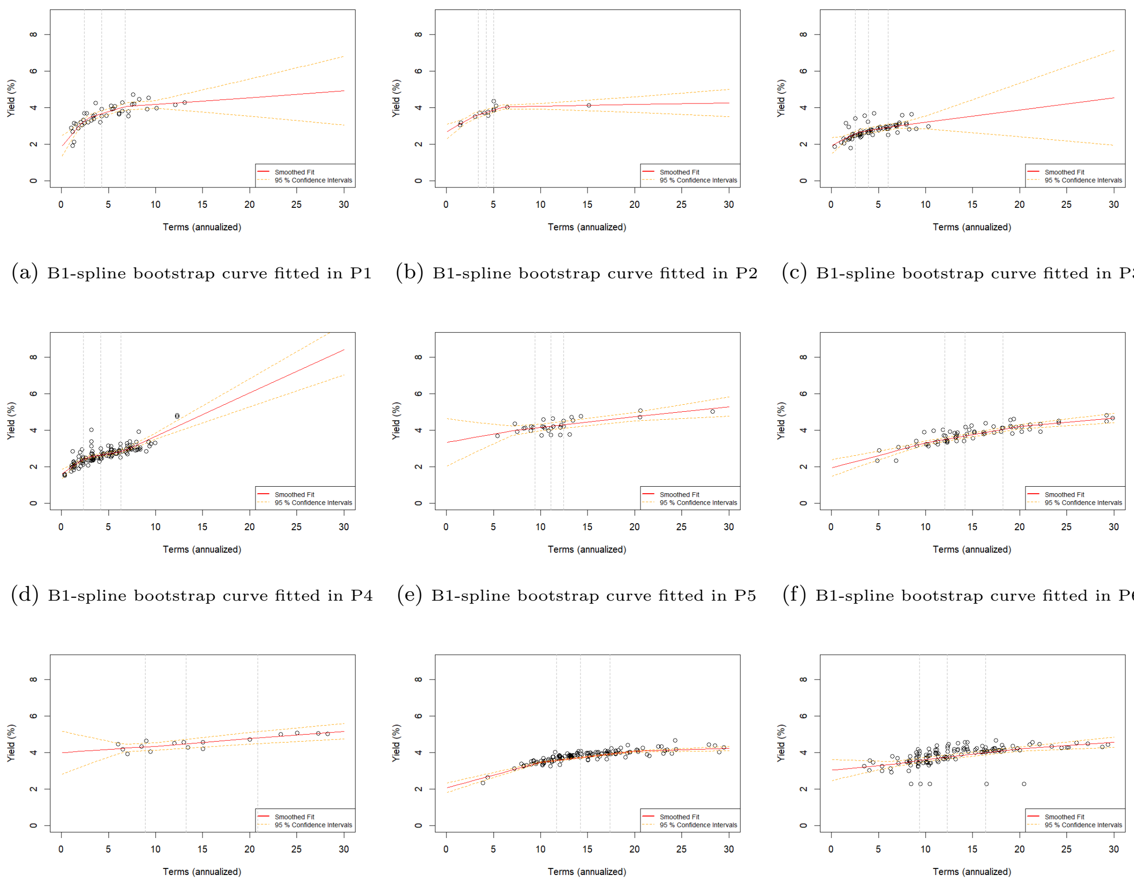
Table 1: Specifications of the green bonds groups used in the bootstrapping application

Partition	Callability	Coupon range	Tax status	No of bonds	Yield Descriptive Summary		
					Mean	Median	St.dev.
P1	Non-Callable	[0.20-3.00)	All	182	4.054	4.649	1.497
P2	Non-Callable	[3.00-5.00)	FTSE	56	3.889	4.599	1.609
P3	Non-Callable	[3.00-5.00)	TE	289	2.649	2.813	0.981
P4	Non-Callable	[5.00-7.69]	All	698	2.562	2.643	1.131
P5	Callable	[1.00-3.50)	FTSE	216	3.502	3.554	0.875
P6	Callable	[1.00-3.50)	TE	81	4.657	4.961	0.988
P7	Callable	[3.50-5.00)	FTSE	448	3.472	3.595	0.676
P8	Callable	[3.50-5.00)	TE	80	4.481	4.876	1.114
P9	Callable	[5.00-8.50]	All	779	3.598	3.724	0.921

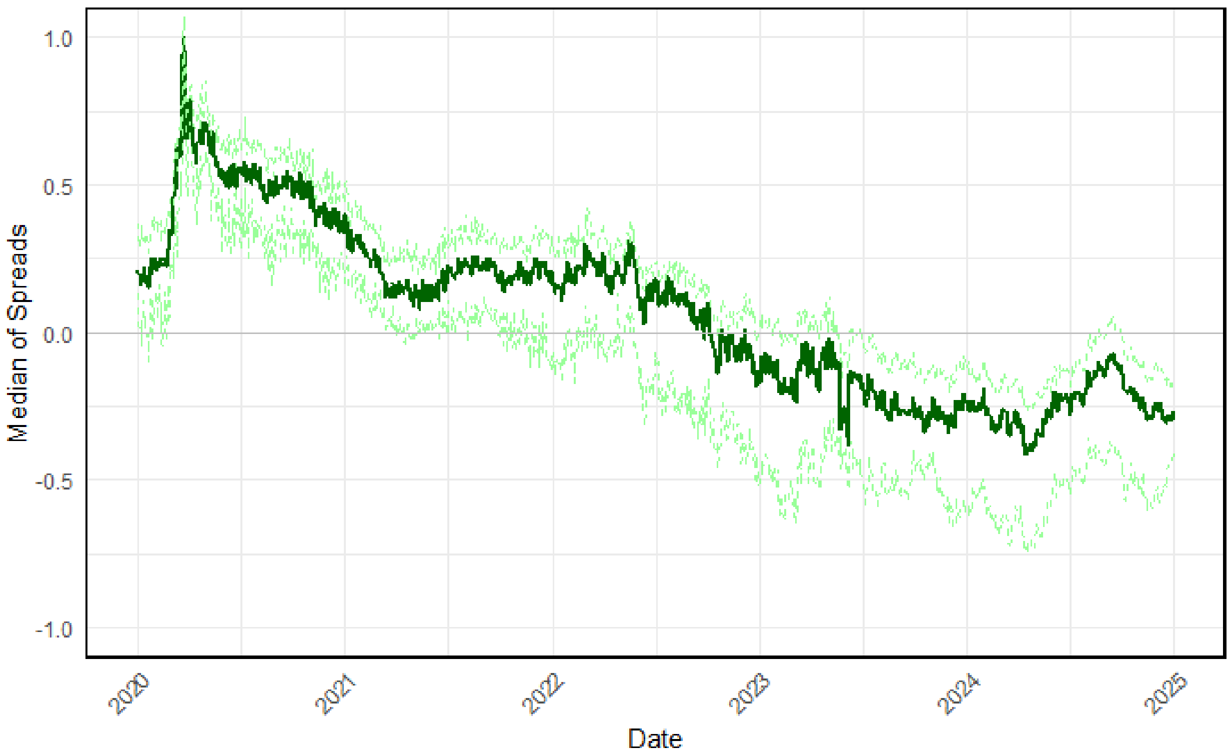


(a) B1-spline bootstrap curve fitted in P1 (b) B1-spline bootstrap curve fitted in P2 (c) B1-spline bootstrap curve fitted in P3

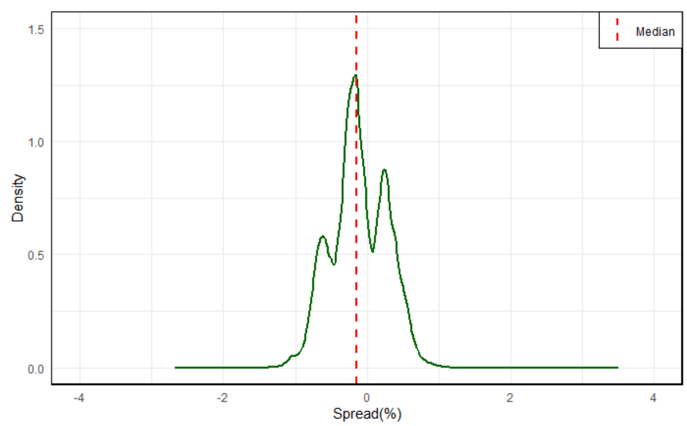
(d) B1-spline bootstrap curve fitted in P4 (e) B1-spline bootstrap curve fitted in P5 (f) B1-spline bootstrap curve fitted in P6

(g) B1-spline bootstrap curve fitted in P7 (h) B1-spline bootstrap curve fitted in P8 (i) B1-spline bootstrap curve fitted in P9

Figure 1: **B1-spline bootstrap curve fitted for bonds partitions 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. Te nine partitions ($P1 - P9$) are detailed in Table 1.



(a) Median of daily green bond yield spreads



(b) Kernel density of green bond yield spreads

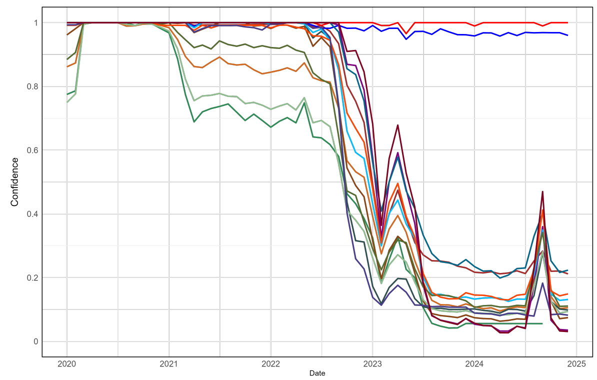
Figure 2: **Green bond yield spreads based on YTM in California (2020-2024)**
The top panel displays the daily median of the green bond yield spreads in California. The green dashed lines represent the 25th and 75th percentiles of the spreads. The bottom panel shows the kernel density estimate of the spread, with the red dashed line indicating the sample median.

Table 2: Descriptive statistics of green bond yield spreads in California (2020–2024).

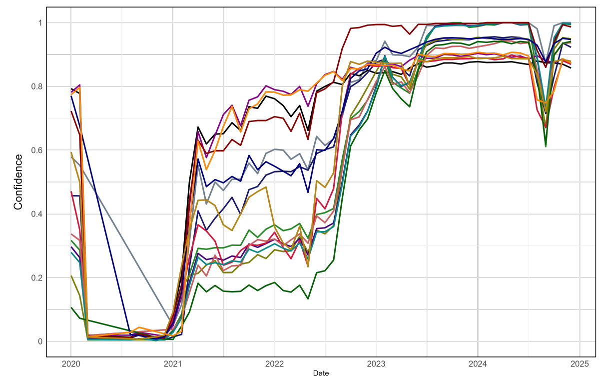
	Descriptive Statistics						
Year	Min	1st Qu.	Median	Mean	3rd Qu.	Max	St. dev.
2020	-0.530	0.270	0.480	0.438	0.610	3.510	0.253
2021	-0.480	0.040	0.200	0.180	0.310	1.280	0.189
2022	-1.160	-0.130	0.100	0.048	0.250	1.250	0.312
2023	-2.680	-0.490	-0.230	-0.238	-0.050	0.920	0.366
2024	-1.360	-0.500	-0.250	-0.260	-0.090	0.480	0.311
Total	-2.680	-0.280	-0.030	-0.027	0.280	3.510	0.397

Table 3: The support, confidence, and lift of first-order attribute associations of positive and negative green bond yield spreads.

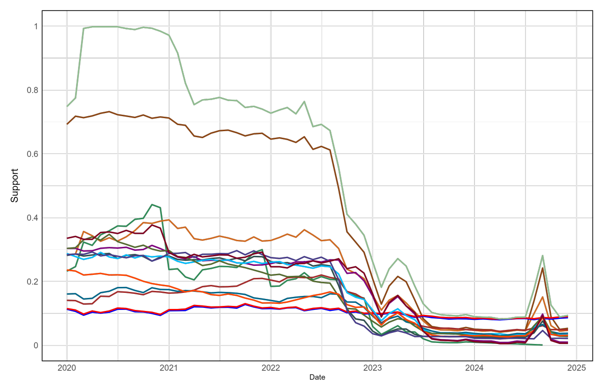
Rank	Rule	Support	Confidence	Lift
Panel A: Positive Spread ($S(+)$)				
1	{Tax : FED TAXABLE/ST TAX-EXEMPT}	0.155	0.966	2.050
2	{Pricing TYP : At Par}	0.149	0.947	2.009
3	{S OID : Higher than 100}	0.163	0.688	1.461
4	{R Ys to Maturity : Higher than 14.4}	0.166	0.673	1.429
5	{Y_OID : Higher than 3.2}	0.155	0.623	1.321
6	{Maturity OID : Higher than 17}	0.154	0.616	1.306
7	{DU_Adj_MID : Higher than 7}	0.151	0.608	1.290
8	{Active years : Less than 1.1}	0.148	0.588	1.247
9	{S OID : 57_100}	0.136	0.573	1.216
10	{Call : Callable}	0.350	0.559	1.185
11	{Y_OID : 2.4_3.2}	0.137	0.547	1.161
12	{Maturity OID : 12.3_17}	0.136	0.544	1.154
13	{R Ys to Maturity : 9.4_14.4}	0.137	0.541	1.147
14	{Self Rep. Gr. : Not labelled}	0.101	0.529	1.122
15	{Issued Amt : Higher than 16}	0.131	0.527	1.118
Panel B: Negative Spread ($S(-)$)				
1	{S OID : Less than 17}	0.183	0.774	1.482
2	{Y_OID : Less than 1.7}	0.181	0.724	1.387
3	{Maturity OID : Less than 8}	0.177	0.706	1.352
4	{R Ys to Maturity : Less than 4.7}	0.177	0.706	1.351
5	{Call : Non-callable}	0.251	0.670	1.283
6	{Pricing TYP : At Premium}	0.479	0.631	1.208
7	{CPN : 5_8.5(%)}	0.303	0.626	1.198
8	{Tax : FED & ST TAX-EXEMPT}	0.492	0.617	1.182
9	{R Ys to Maturity : 4.7_9.4}	0.153	0.611	1.170
10	{Active years : Higher than 4.1}	0.152	0.609	1.167
11	{DU_Adj_MID : Less than 2.8}	0.148	0.596	1.142
12	{S OID : 17_57}	0.139	0.585	1.121
13	{Issued Amt : Less than 14}	0.146	0.584	1.118
14	{DU_Adj_MID : 2.8_4.8}	0.141	0.566	1.084
15	{Maturity OID : 8_12.3}	0.140	0.559	1.071



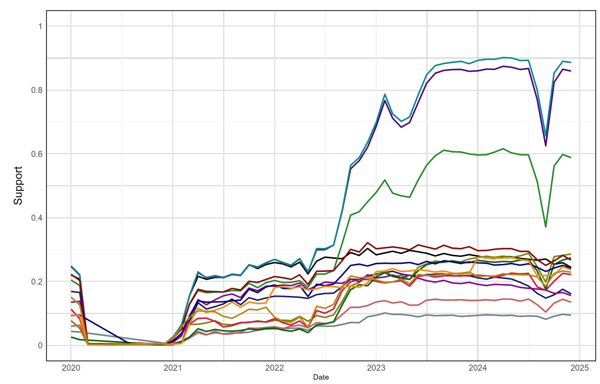
(a) Positive Spread - Confidence



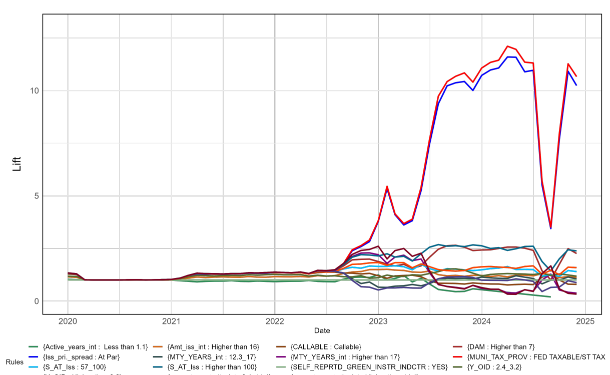
(b) Negative Spread - Confidence



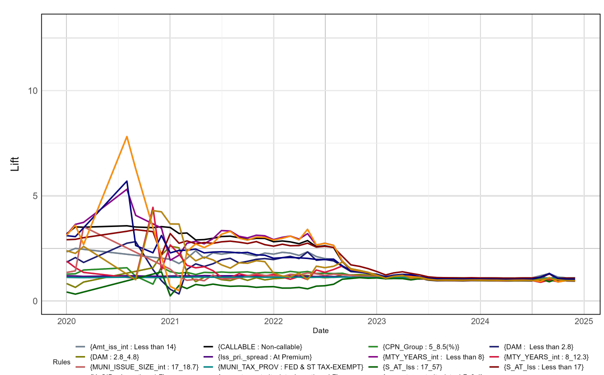
(c) Positive Spread - Support



(d) Negative Spread - Support



(e) Positive Spread - Lift



(f) Negative Spread - Lift

Figure 3: Temporal evolution of confidence, support, and lift for positive (left) and negative (right) green bond yield-spread rules. Each row tracks a different association-rule metric over time: the top row shows rule confidence, the middle row shows rule support, and the bottom row shows rule lift. Within each panel, colored lines correspond to the ten highest-ranked antecedent conditions for positive spreads (left panels) and negative spreads (right panels).

Table 4: Summary of purchasing-bond characteristics and matched curve partitions for groups G1–G4

Group	Synthetic Purchasing Bonds Characteristics			Curve Partition
	Coupon	Callability	Tax Status	
G1	2.5%	non-callable	FED TAXABLE/ST TAX-EXEMPT	P1
G2	3.5%	non-callable	FED TAXABLE/ST TAX-EXEMPT	P2
G3	5.5%	non-callable	FED TAXABLE	P4
G4	4.0%	non-callable	FED & ST TAX-EXEMPT	P3

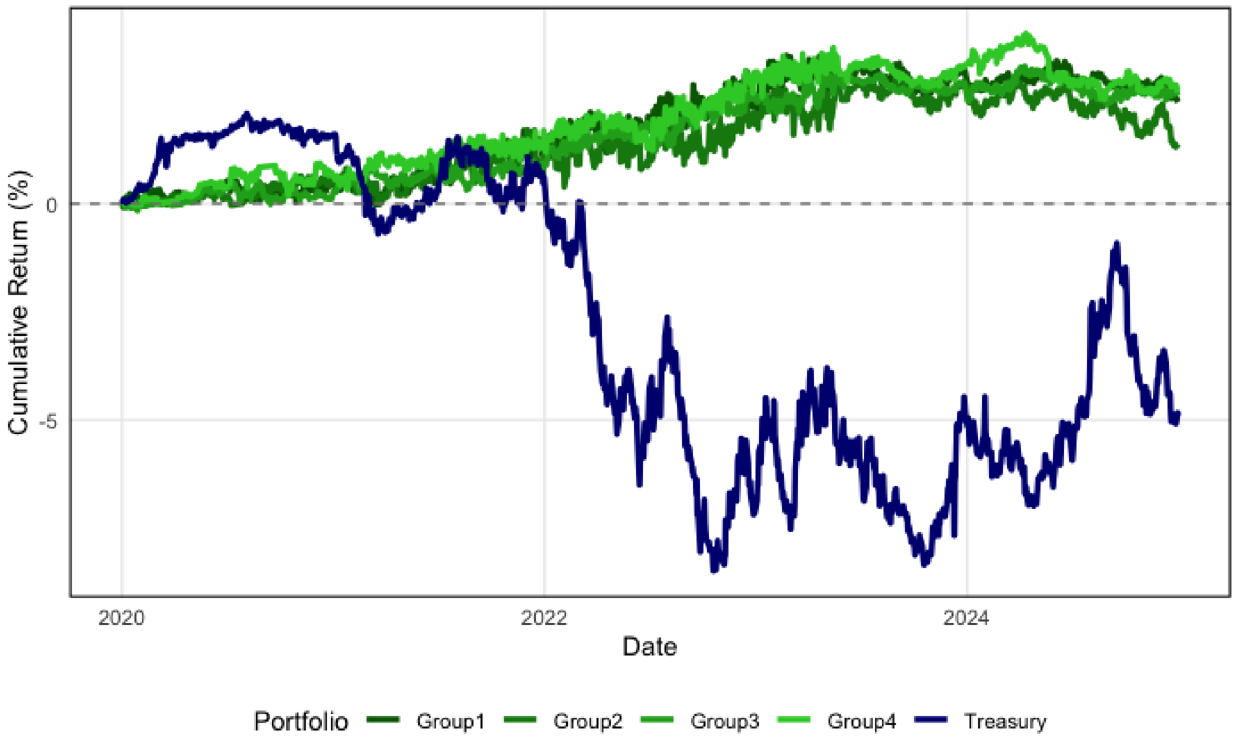


Figure 4: Cumulative return paths for the screened portfolios (Group1–Group4) and the Treasury benchmark over the 2020–2024 period.

Table 5: Homogeneous portfolio performance metrics (2020–2024)

Portfolio	2020				2021				2022				2023				2024				Overall			
	Return (%)	Sharpe	Sortino	Max DD (%)	Return (%)	Sharpe	Sortino	Max DD (%)	Return (%)	Sharpe	Sortino	Max DD (%)	Return (%)	Sharpe	Sortino	Max DD (%)	Return (%)	Sharpe	Sortino	Max DD (%)	Return (%)	Sharpe	Sortino	Max DD (%)
Group 1	0.425	-0.604	-0.822	-0.492	1.040	0.034	0.047	-0.613	1.045	0.035	0.060	-0.938	0.621	-0.133	-0.189	-1.030	-0.381	-1.399	-1.861	-0.923	2.351	-0.232	-0.318	-1.039
Group 2	0.524	-0.520	-0.708	-0.370	0.616	-0.159	-0.223	-1.028	0.512	-0.130	-0.199	-1.159	0.774	-0.075	-0.094	-1.154	-1.288	-1.488	-2.277	-1.476	1.284	-0.320	-0.430	-1.539
Group 3	0.265	-1.028	-1.399	-0.521	0.609	-0.348	-0.527	-0.541	1.595	0.357	0.640	-0.639	0.392	-0.425	-0.629	-0.623	0.120	-0.654	-1.039	-0.849	2.504	-0.373	-0.544	-0.849
Group 4	0.657	-0.335	-0.459	-0.679	0.802	-0.085	-0.136	-0.550	1.819	0.339	0.541	-0.857	0.163	-0.383	-0.537	-0.881	-0.625	-1.381	-1.707	-1.454	2.595	-0.248	-0.346	-1.454
Treasury	1.600	0.544	0.751	-0.711	-0.981	-0.842	-1.323	-2.264	-7.229	-1.675	-2.839	-8.572	2.159	0.238	0.431	-4.730	0.264	-0.153	-0.223	-4.213	-4.901	-0.482	-0.698	-10.361

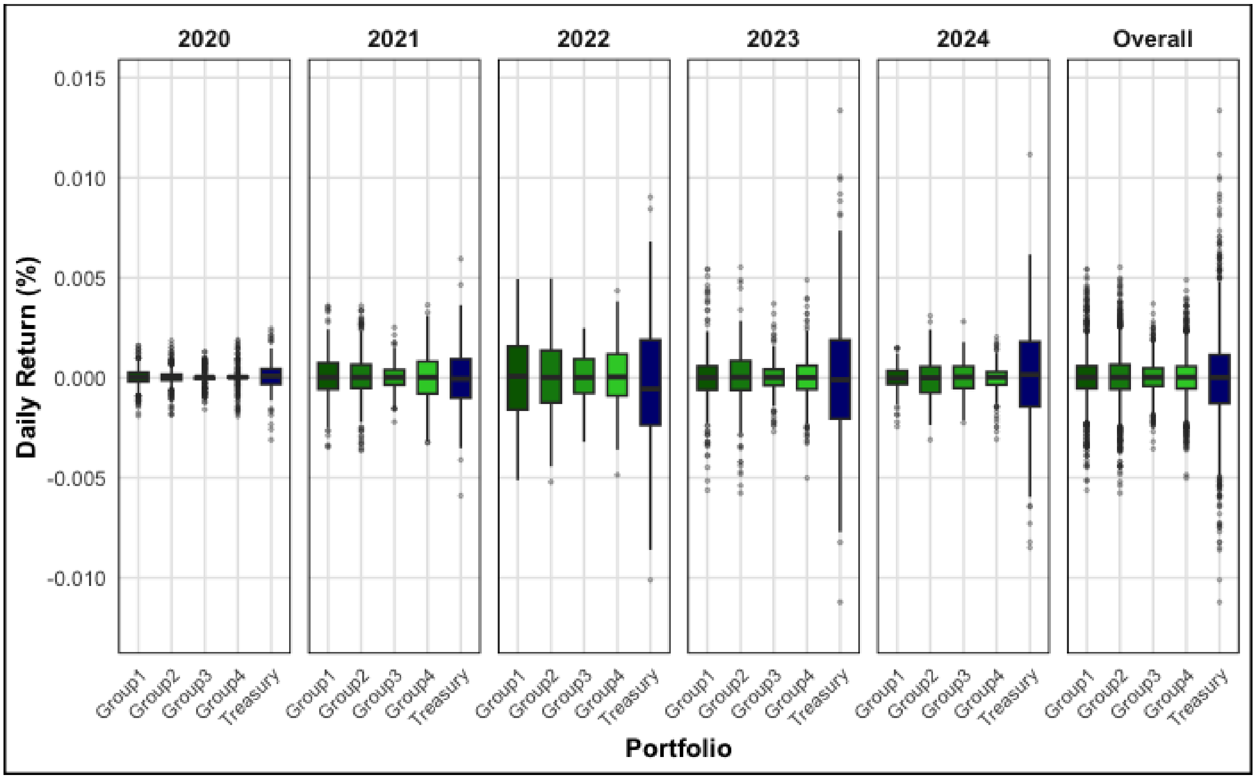
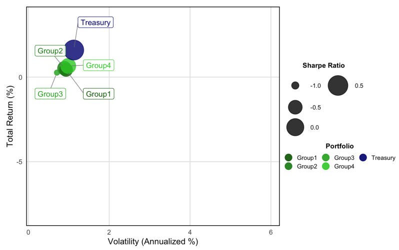
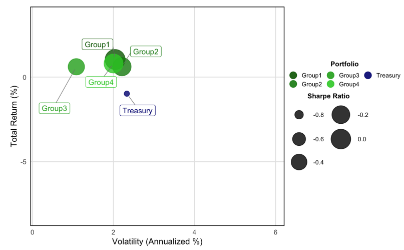


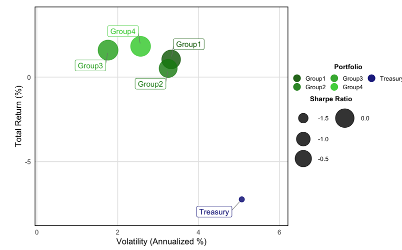
Figure 5: Daily return distributions for the screened portfolios (Group1–Group4) and the Treasury benchmark, shown separately for each year from 2020 to 2024 and for the overall sample period.



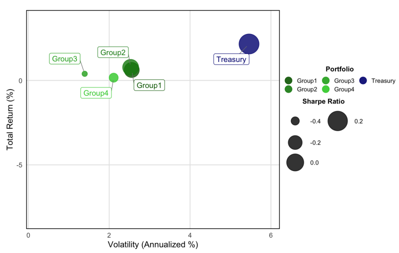
(a) 2020: Total return vs. annualized volatility with Sharpe-scaled bubbles.



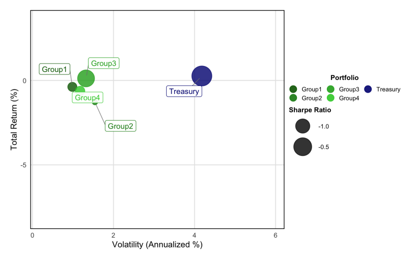
(b) 2021: Total return vs. annualized volatility with Sharpe-scaled bubbles.



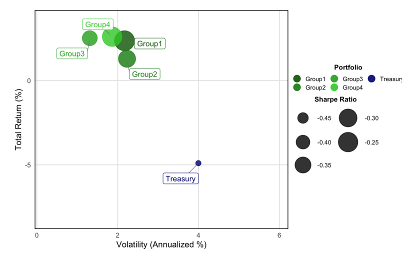
(c) 2022: Total return vs. annualized volatility with Sharpe-scaled bubbles.



(d) 2023: Total return vs. annualized volatility with Sharpe-scaled bubbles.



(e) 2024: Total return vs. annualized volatility with Sharpe-scaled bubbles.

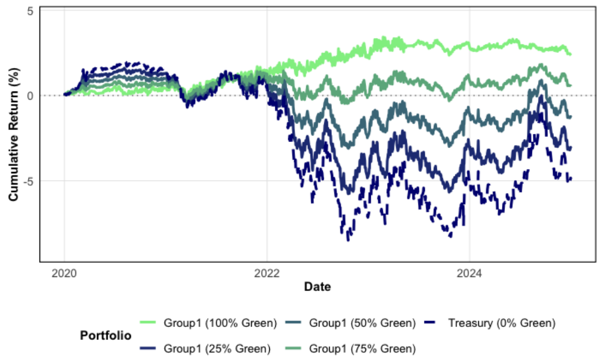


(f) Overall: Total return vs. annualized volatility with Sharpe-scaled bubbles.

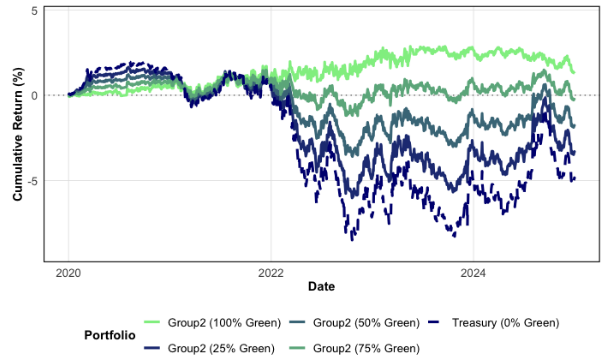
Figure 6: Risk–return scatter plots for screened portfolios and the Treasury benchmark across individual years (2020–2024) and the overall sample period. Each subfigure displays total return (vertical axis) against annualized volatility (horizontal axis), with bubble size proportional to the absolute Sharpe ratio. Bubble size represents Sharpe ratio, with larger bubbles indicating superior risk-adjusted returns. Size is linearly scaled to enable visual comparison of portfolio efficiency across different risk-return profiles.

Table 6: Hybrid Portfolio Performance: 10 years Tenor-Based Portfolios (Groups 1–4, 2020–2024)

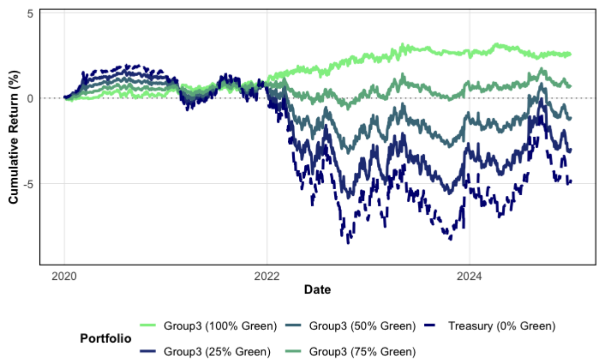
Portfolio	2020				2021				2022				2023				2024				Overall			
	Return (%)	Sharpe	Sortino	Max DD (%)	Return (%)	Sharpe	Sortino	Max DD (%)	Return (%)	Sharpe	Sortino	Max DD (%)	Return (%)	Sharpe	Sortino	Max DD (%)	Return (%)	Sharpe	Sortino	Max DD (%)	Return (%)	Sharpe	Sortino	Max DD (%)
Group 1 (100%)	0.425	-0.604	-0.822	-0.492	1.040	0.034	0.047	-0.613	1.045	0.035	0.060	-0.938	0.621	-0.133	-0.189	-1.030	-0.381	-1.399	-1.861	-0.923	2.351	-0.232	-0.318	-1.039
Group 1 (75%)	0.719	-0.358	-0.496	-0.393	0.531	-0.268	-0.396	-0.932	-1.005	-0.726	-1.263	-1.886	0.979	0.004	0.007	-1.712	-0.230	-0.838	-1.187	-1.265	0.538	-0.453	-0.650	-1.886
Group 1 (50%)	1.012	0.031	0.045	-0.385	0.024	-0.600	-0.957	-1.358	-3.067	-1.421	-2.409	-4.040	1.354	0.136	0.240	-2.666	-0.072	-0.461	-0.673	-2.197	-1.275	-0.547	-0.799	-4.331
Group 1 (25%)	1.306	0.361	0.505	-0.514	-0.480	-0.790	-1.260	-1.812	-5.142	-1.663	-2.795	-6.246	1.747	0.204	0.368	-3.680	0.093	-0.267	-0.389	-3.196	-3.088	-0.526	-0.761	-7.254
Group 2 (100%)	0.524	-0.520	-0.708	-0.370	0.616	-0.159	-0.223	-1.028	0.512	-0.130	-0.199	-1.159	0.774	-0.075	-0.094	-1.154	-1.288	-1.488	-2.277	-1.476	1.284	-0.320	-0.430	-1.539
Group 2 (75%)	0.793	-0.265	-0.354	-0.264	0.214	-0.445	-0.665	-1.025	-1.405	-0.868	-1.460	-2.394	1.097	0.054	0.085	-1.375	-0.922	-1.047	-1.534	-1.749	-0.263	-0.514	-0.734	-2.644
Group 2 (50%)	1.062	0.098	0.138	-0.325	-0.187	-0.756	-1.250	-1.321	-3.335	-1.474	-2.435	-4.267	1.435	0.161	0.300	-2.266	-0.542	-0.615	-0.887	-2.506	-1.809	-0.577	-0.852	-4.860
Group 2 (25%)	1.331	0.385	0.527	-0.503	-0.585	-0.875	-1.395	-1.792	-5.276	-1.672	-2.760	-6.392	1.789	0.212	0.399	-3.408	-0.147	-0.333	-0.484	-3.353	-3.355	-0.537	-0.785	-7.549
Group 3 (100%)	0.265	-1.028	-1.399	-0.521	0.609	-0.348	-0.527	-0.541	1.595	0.357	0.640	-0.639	0.392	-0.425	-0.629	-0.623	0.120	-0.654	-1.039	-0.849	2.504	-0.373	-0.544	-0.849
Group 3 (75%)	0.598	-0.670	-0.922	-0.372	0.208	-0.777	-1.238	-0.608	-0.598	-0.839	-1.337	-1.789	0.803	-0.104	-0.170	-1.531	0.154	-0.560	-0.913	-1.094	0.653	-0.602	-0.877	-1.789
Group 3 (50%)	0.932	-0.089	-0.133	-0.410	-0.191	-0.914	-1.389	-1.020	-2.799	-1.425	-2.246	-3.979	1.234	0.100	0.180	-2.560	0.189	-0.356	-0.530	-2.101	-1.199	-0.584	-0.843	-4.372
Group 3 (25%)	1.266	0.324	0.463	-0.561	-0.587	-0.888	-1.361	-1.611	-5.010	-1.612	-2.694	-6.240	1.686	0.189	0.344	-3.626	0.226	-0.229	-0.336	-3.142	-3.050	-0.527	-0.763	-7.380
Group 4 (100%)	0.657	-0.335	-0.459	-0.679	0.802	-0.085	-0.136	-0.550	1.819	0.339	0.541	-0.857	0.163	-0.383	-0.537	-0.881	-0.625	-1.381	-1.707	-1.454	2.595	-0.248	-0.346	-1.454
Group 4 (75%)	0.893	-0.123	-0.158	-0.527	0.353	-0.395	-0.617	-0.613	-0.424	-0.608	-1.075	-1.886	0.626	-0.175	-0.272	-1.638	-0.417	-0.961	-1.398	-1.150	0.721	-0.490	-0.719	-1.903
Group 4 (50%)	1.128	0.188	0.254	-0.458	-0.094	-0.717	-1.123	-0.955	-2.680	-1.331	-2.239	-4.064	1.111	0.055	0.096	-2.632	-0.200	-0.528	-0.782	-2.095	-1.153	-0.559	-0.809	-4.480
Group 4 (25%)	1.364	0.429	0.585	-0.550	-0.538	-0.848	-1.336	-1.605	-4.948	-1.600	-2.700	-6.280	1.622	0.175	0.311	-3.662	0.027	-0.291	-0.423	-3.144	-3.027	-0.526	-0.756	-7.390
Treasury (0%)	1.600	0.544	0.751	-0.711	-0.981	-0.842	-1.323	-2.264	-7.229	-1.675	-2.839	-8.572	2.159	0.238	0.431	-4.730	0.264	-0.153	-0.223	-4.213	-4.901	-0.482	-0.698	-10.361



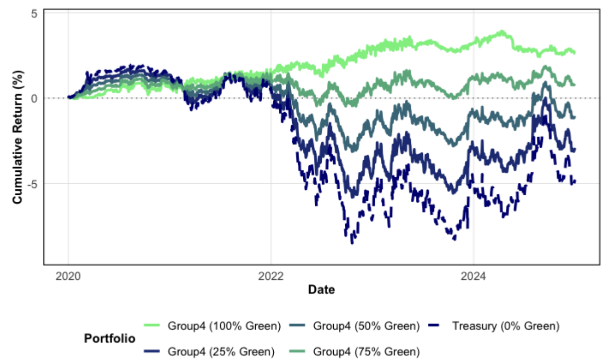
(a) Cumulative returns for Group 1 screened portfolios and Treasury.



(b) Cumulative returns for Group 2 screened portfolios and Treasury.

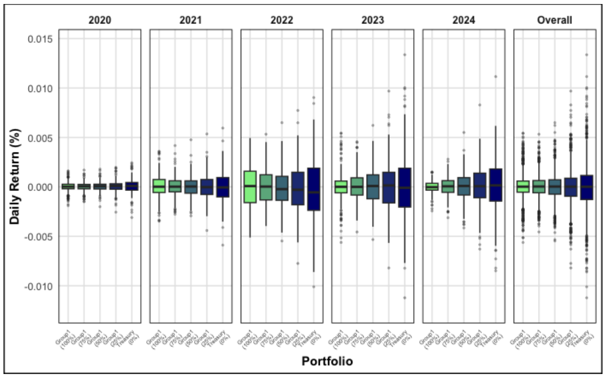


(c) Cumulative returns for Group 3 screened portfolios and Treasury.

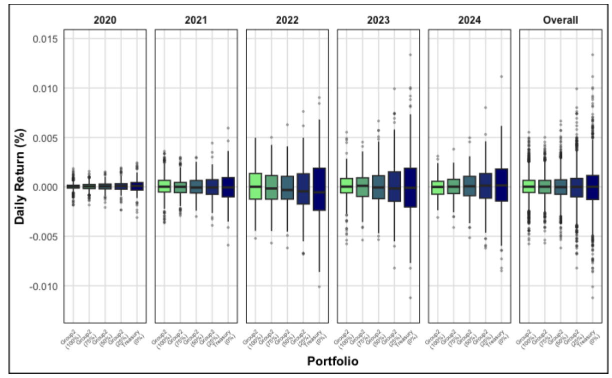


(d) Cumulative returns for Group 4 screened portfolios and Treasury.

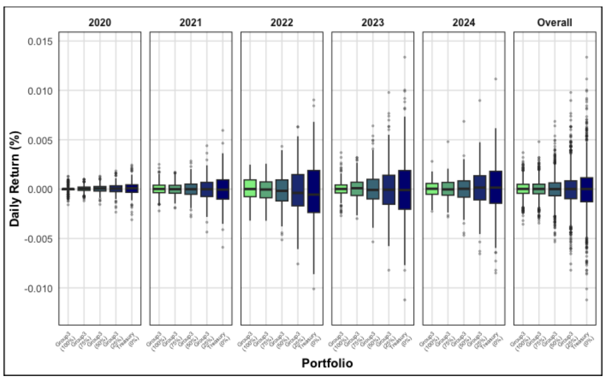
Figure 7: Cumulative performance of screened green bond portfolios (100%, 75%, 50%, 25% green allocation) compared with the Treasury benchmark (0% green) for Groups 1–4.



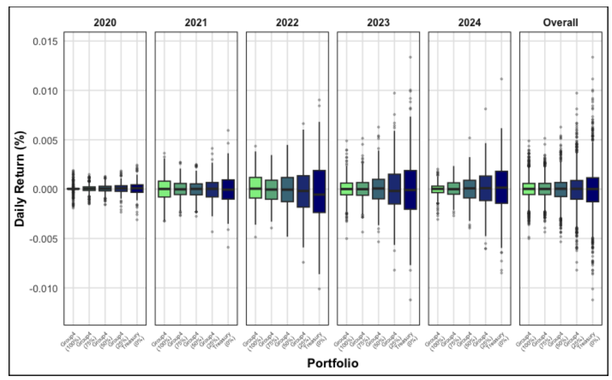
(a) Daily return distributions for Group 1 hybrid portfolios (2020–2024 and overall).



(b) Daily return distributions for Group 2 hybrid portfolios across all years.



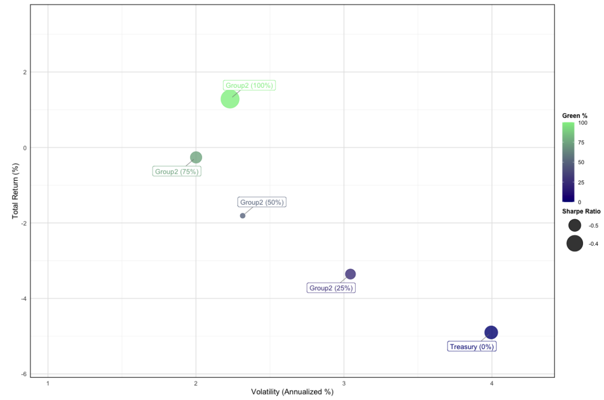
(c) Daily return distributions for Group 3 hybrid portfolios (yearly and overall).



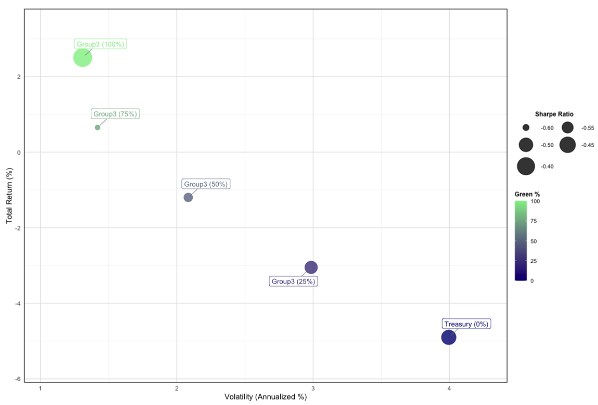
(d) Daily return distributions for Group 4 hybrid portfolios across sample years.

Figure 8: Daily return box-plots for the hybrid green bond portfolios (Groups 1–4). Each panel shows distributions for 2020–2024 and overall.

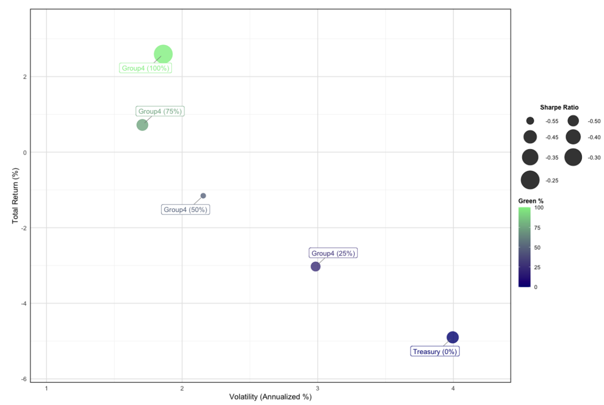
(a) Group 1 hybrid portfolios: total return vs. volatility with Sharpe-scaled marker size and green share–based color.



(b) Group 2 hybrid portfolios: performance–risk trade-off across increasing green allocation weights.



(c) Group 3 hybrid portfolios: annualized volatility vs. overall return, colored by green intensity.

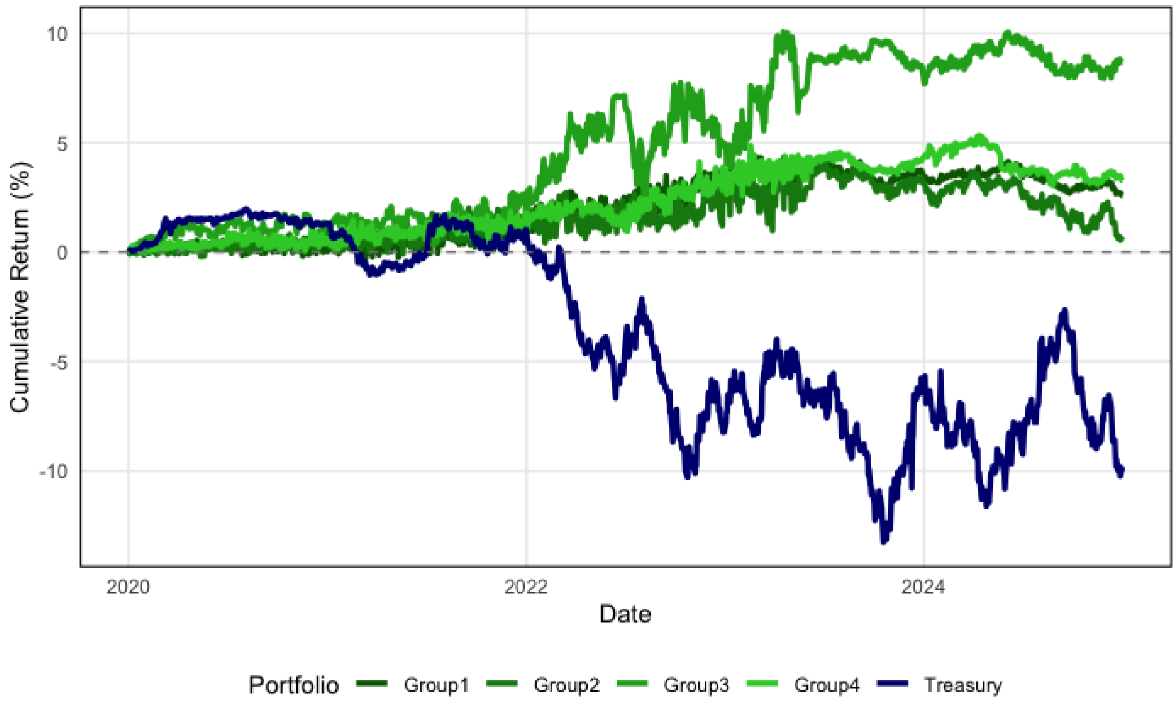


(d) Group 4 hybrid portfolios: relative position of green-weighted strategies compared with Treasury.

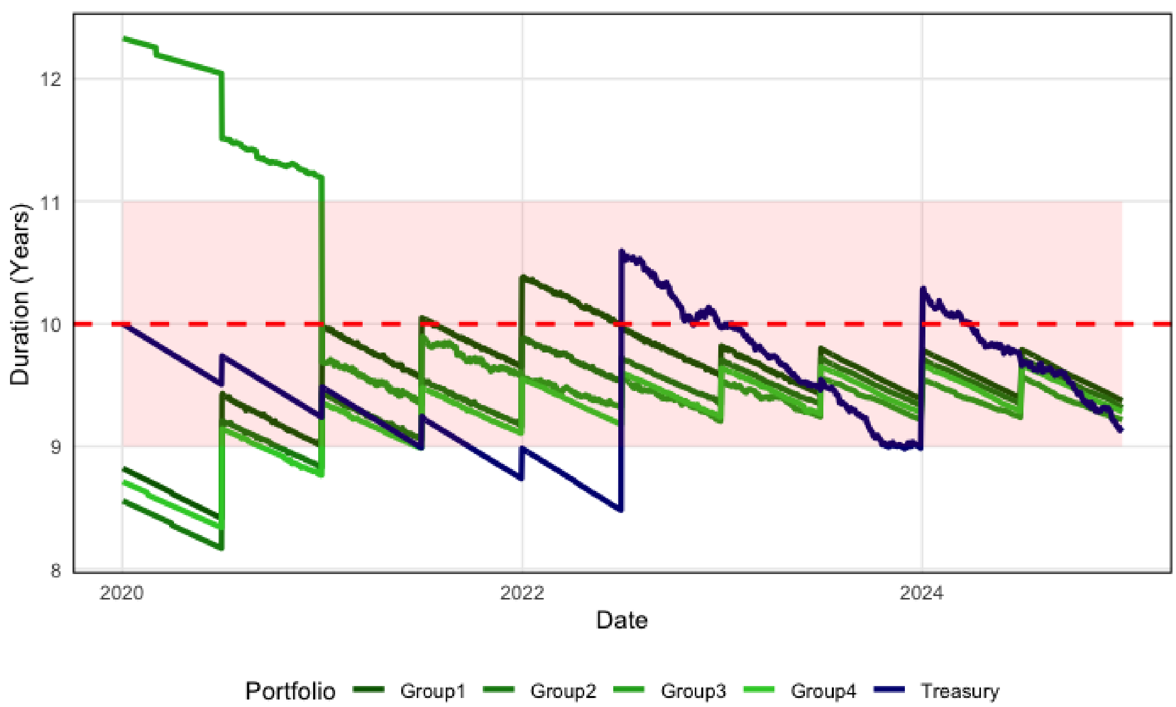
Figure 9: Comparative risk–return scatter plots for hybrid portfolios in Groups 1–4, showing annualized volatility (x-axis), total return (y-axis), marker size proportional to Sharpe ratio, and marker color based on percentage of green allocation. Bubble size represents Sharpe ratio, with larger bubbles indicating superior risk-adjusted returns. Size is linearly scaled to enable visual comparison of portfolio efficiency across different risk-return profiles.

Table 7: Portfolio Performance Metrics by Year and Overall for duration-based portfolios (2020–2024)

Portfolio	2020				2021				2022				2023				2024				Overall			
	Return (%)	Sharpe	Sortino	Max DD (%)	Return (%)	Sharpe	Sortino	Max DD (%)	Return (%)	Sharpe	Sortino	Max DD (%)	Return (%)	Sharpe	Sortino	Max DD (%)	Return (%)	Sharpe	Sortino	Max DD (%)	Return (%)	Sharpe	Sortino	Max DD (%)
Group1	0.022	-0.327	-0.568	-0.789	1.169	0.059	0.101	-1.239	1.503	0.111	0.178	-1.660	0.276	-0.133	-0.162	-1.882	-0.732	-1.248	-1.718	-1.479	2.597	-0.081	-0.109	-1.882
Group2	0.527	-0.153	-0.219	-0.821	0.055	-0.115	-0.203	-1.600	0.699	0.004	0.008	-2.038	0.544	-0.038	-0.050	-2.392	-2.478	-1.269	-1.928	-3.034	0.529	-0.128	-0.183	-3.383
Group3	0.904	-0.027	-0.038	-1.103	0.501	-0.116	-0.163	-2.293	2.113	0.197	0.296	-4.278	3.377	0.469	0.666	-3.335	0.906	-0.014	-0.023	-1.907	8.676	0.172	0.234	-4.278
Group4	0.567	-0.131	-0.200	-0.968	0.847	-0.011	-0.016	-1.209	2.406	0.316	0.595	-1.452	0.513	-0.057	-0.072	-2.039	-1.057	-1.074	-1.328	-2.176	3.278	-0.062	-0.086	-2.176
Treasury	1.312	0.279	0.386	-0.827	-0.270	-0.493	-0.877	-2.334	-8.743	-1.679	-3.021	-10.789	1.579	0.111	0.195	-9.657	-4.285	-0.674	-0.981	-7.798	-10.017	-0.508	-0.704	-14.943



(a) Cumulative returns of the four screened portfolios compared with the Treasury benchmark (2020–2024).



(b) Evolution of portfolio durations relative to the 10-year duration target, highlighting the rebalancing pattern for each group.

Figure 10: Performance and duration dynamics of screened green-bond portfolios and the Treasury benchmark (2020–2024).

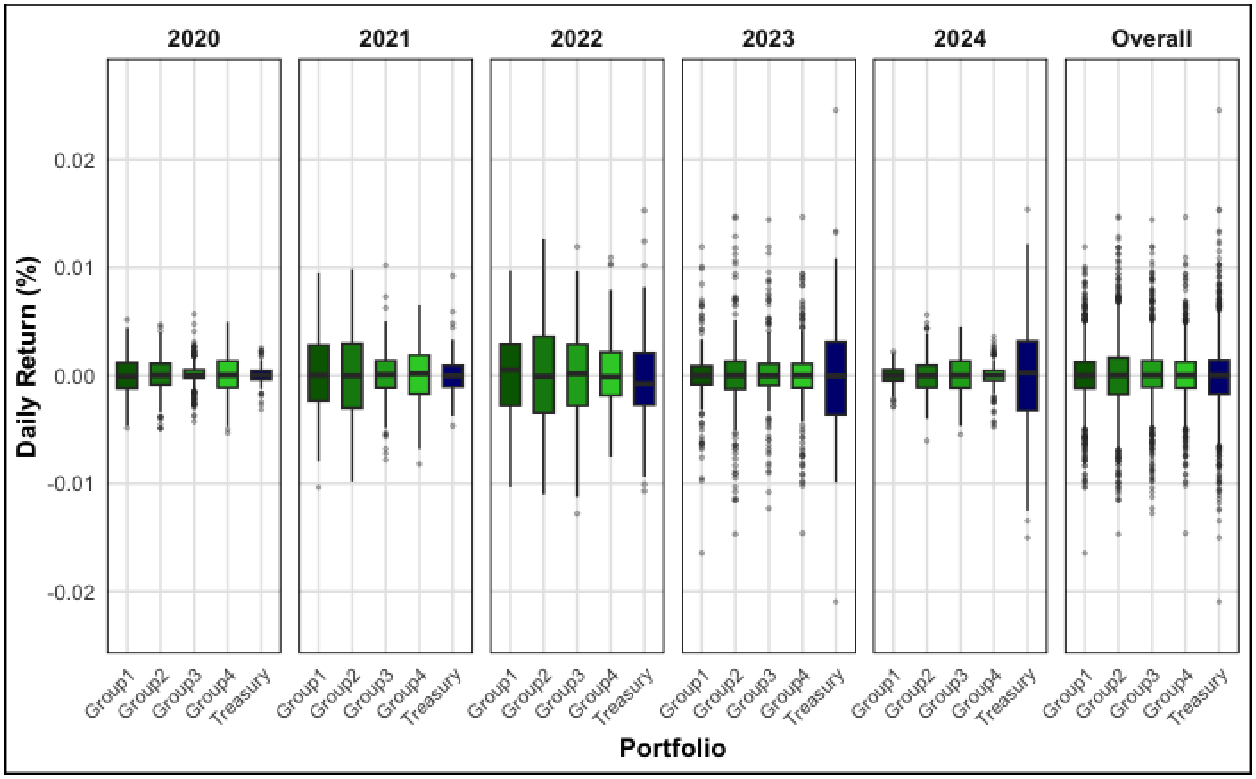
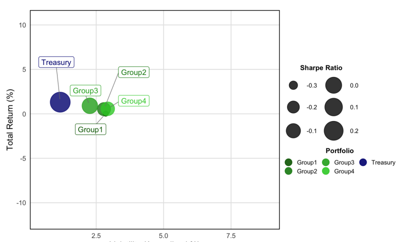
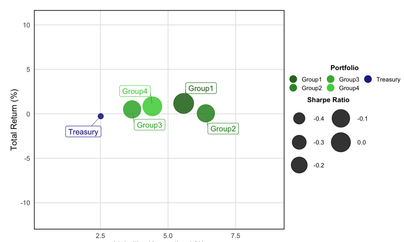


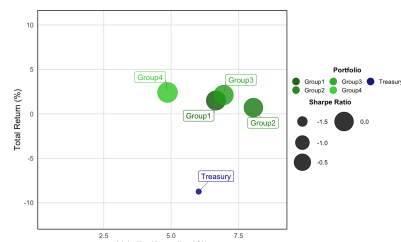
Figure 11: Distribution of daily returns (2020–2024) for the duration-based screened portfolios (Groups 1–4) and the Treasury benchmark. Each panel shows the annual return dispersion, with the final panel summarizing the overall period.



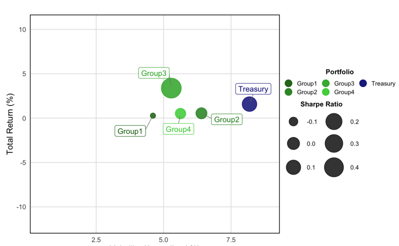
(a) 2020 Performance



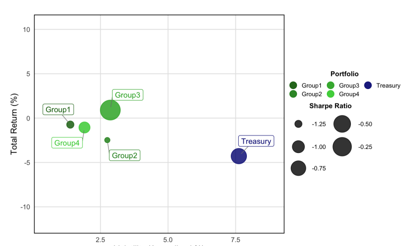
(b) 2021 Performance



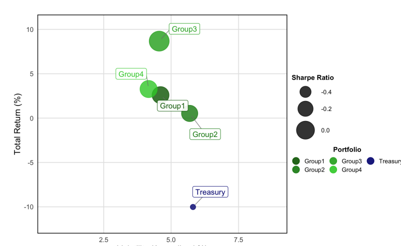
(c) 2022 Performance



(d) 2023 Performance



(e) 2024 Performance

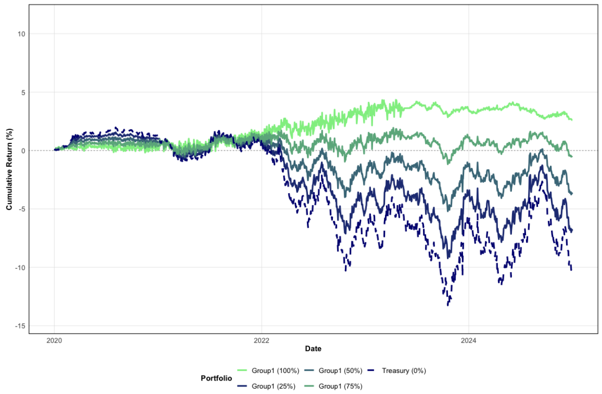


(f) Overall Performance

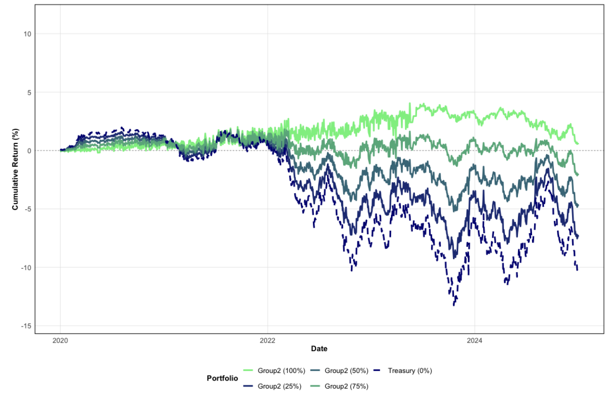
Figure 12: Comparative return–volatility profiles of duration-based hybrid portfolios (2020–2024 and overall). Bubble size represents Sharpe ratio, with larger bubbles indicating superior risk-adjusted returns. Size is linearly scaled to enable visual comparison of portfolio efficiency across different risk-return profiles.

Table 8: Hybrid Portfolio Performance: Duration-Based Portfolios, 2020–2024)

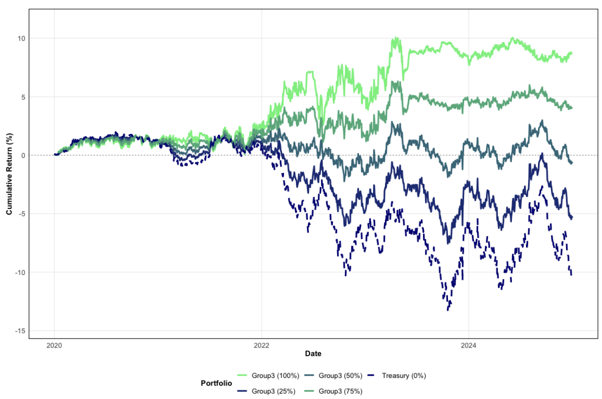
Portfolio	2020				2021				2022				2023				2024				Overall			
	Return	Sharpe	Sortino	Max DD	Return	Sharpe	Sortino	Max DD	Return	Sharpe	Sortino	Max DD	Return	Sharpe	Sortino	Max DD	Return	Sharpe	Sortino	Max DD	Return	Sharpe	Sortino	Max DD
	(%)			(%)	(%)			(%)	(%)			(%)	(%)			(%)	(%)			(%)	(%)			(%)
Group 1 (100%)	0.022	-0.327	-0.568	-0.789	1.169	0.059	0.101	-1.239	1.503	0.111	0.178	-1.660	0.276	-0.133	-0.162	-1.882	-0.732	-1.248	-1.718	-1.479	2.597	-0.081	-0.109	-1.882
Group 1 (75%)	0.345	-0.290	-0.503	-0.681	0.806	-0.023	-0.039	-1.278	-1.040	-0.363	-0.592	-2.631	0.574	-0.089	-0.118	-3.063	-1.558	-1.089	-1.584	-2.143	-0.557	-0.276	-0.397	-3.063
Group 1 (50%)	0.667	-0.203	-0.359	-0.581	0.445	-0.164	-0.271	-1.501	-3.595	-1.024	-1.780	-5.095	0.890	-0.002	-0.003	-5.052	-2.424	-0.869	-1.274	-3.888	-3.710	-0.463	-0.688	-6.477
Group 1 (25%)	0.990	0.003	0.006	-0.632	0.086	-0.376	-0.642	-1.778	-6.163	-1.541	-2.785	-7.861	1.224	0.068	0.116	-7.295	-3.332	-0.749	-1.096	-5.816	-6.863	-0.527	-0.745	-10.627
Group 2 (100%)	0.527	-0.153	-0.219	-0.821	0.055	-0.115	-0.203	-1.600	0.699	0.004	0.008	-2.038	0.544	-0.038	-0.050	-2.392	-2.478	-1.269	-1.928	-3.034	0.529	-0.128	-0.183	-3.383
Group 2 (75%)	0.723	-0.117	-0.170	-0.695	-0.027	-0.187	-0.327	-1.299	-1.642	-0.395	-0.695	-3.266	0.783	-0.013	-0.018	-2.916	-2.899	-1.203	-1.764	-3.106	-2.107	-0.286	-0.426	-3.895
Group 2 (50%)	0.920	-0.041	-0.061	-0.649	-0.108	-0.305	-0.527	-1.576	-3.996	-0.994	-1.821	-5.416	1.034	0.033	0.056	-4.649	-3.340	-0.984	-1.411	-4.490	-4.744	-0.454	-0.682	-6.791
Group 2 (25%)	1.116	0.117	0.172	-0.732	-0.189	-0.471	-0.811	-1.941	-6.363	-1.544	-2.762	-7.992	1.299	0.079	0.137	-7.107	-3.801	-0.803	-1.157	-6.096	-7.380	-0.529	-0.746	-10.731
Group 3 (100%)	0.904	-0.027	-0.038	-1.103	0.501	-0.116	-0.163	-2.293	2.113	0.197	0.296	-4.278	3.377	0.469	0.666	-3.335	0.906	-0.014	-0.023	-1.907	8.676	0.172	0.234	-4.278
Group 3 (75%)	1.006	0.017	0.023	-0.922	0.308	-0.232	-0.336	-1.885	-0.556	-0.250	-0.369	-2.934	2.970	0.446	0.703	-2.665	-0.264	-0.429	-0.681	-2.060	4.003	-0.035	-0.049	-2.934
Group 3 (50%)	1.108	0.097	0.148	-0.742	0.115	-0.396	-0.627	-1.619	-3.255	-0.884	-1.322	-4.424	2.536	0.337	0.598	-4.615	-1.513	-0.634	-0.984	-3.630	-0.670	-0.289	-0.409	-4.615
Group 3 (25%)	1.210	0.213	0.319	-0.710	-0.078	-0.517	-0.898	-1.725	-5.984	-1.458	-2.334	-7.197	2.073	0.204	0.354	-7.031	-2.850	-0.677	-1.014	-5.655	-5.344	-0.453	-0.623	-9.209
Group 4 (100%)	0.567	-0.131	-0.200	-0.968	0.847	-0.011	-0.016	-1.209	2.406	0.316	0.595	-1.452	0.513	-0.057	-0.072	-2.039	-1.057	-1.074	-1.328	-2.176	3.278	-0.062	-0.086	-2.176
Group 4 (75%)	0.753	-0.097	-0.149	-0.814	0.566	-0.111	-0.166	-1.228	-0.370	-0.327	-0.651	-2.356	0.757	-0.029	-0.040	-2.682	-1.802	-1.116	-1.618	-2.144	-0.046	-0.276	-0.410	-2.682
Group 4 (50%)	0.939	-0.025	-0.040	-0.728	0.286	-0.275	-0.432	-1.338	-3.153	-1.098	-2.008	-5.041	1.015	0.027	0.043	-4.767	-2.586	-0.908	-1.364	-3.839	-3.369	-0.468	-0.693	-6.264
Group 4 (25%)	1.126	0.122	0.187	-0.707	0.007	-0.457	-0.842	-1.753	-5.944	-1.552	-2.703	-7.798	1.288	0.078	0.134	-7.096	-3.413	-0.766	-1.118	-5.788	-6.693	-0.525	-0.734	-10.494
Treasury	1.312	0.279	0.386	-0.827	-0.270	-0.493	-0.877	-2.334	-8.743	-1.679	-3.021	-10.789	1.579	0.111	0.195	-9.657	-4.285	-0.674	-0.981	-7.798	-10.017	-0.508	-0.704	-14.943



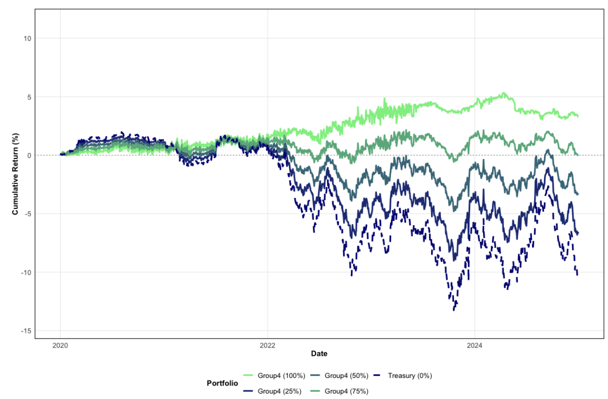
(a) Cumulative return paths for Group 1 hybrid portfolios (25–100%).



(b) Cumulative return paths for Group 2 hybrid portfolios (25–100%).

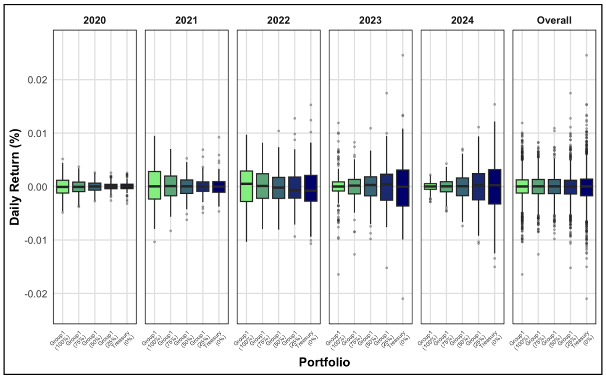


(c) Cumulative return paths for Group 3 hybrid portfolios (25–100%).

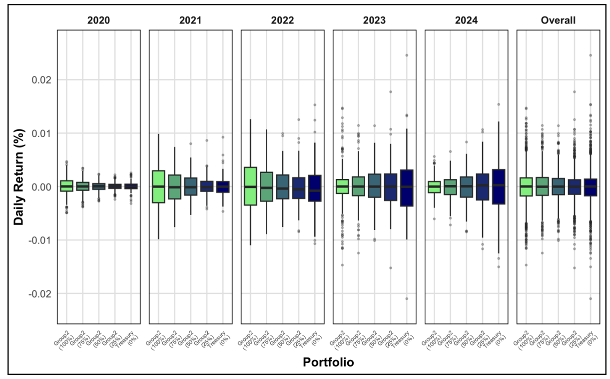


(d) Cumulative return paths for Group 4 hybrid portfolios (25–100%).

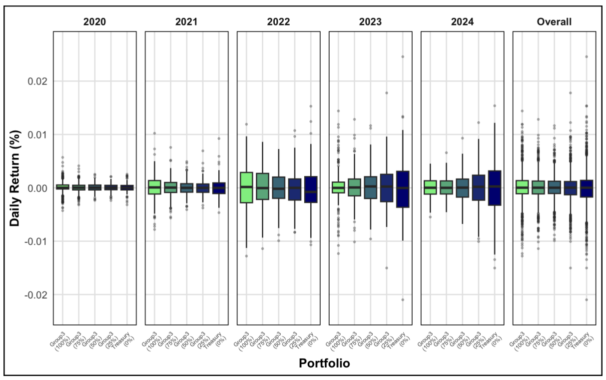
Figure 13: Cumulative return comparison of duration-based hybrid green–Treasury portfolios for Groups 1–4 from 2020 to 2024. Each panel displays portfolio paths at 25%, 50%, 75%, and 100% green allocation.



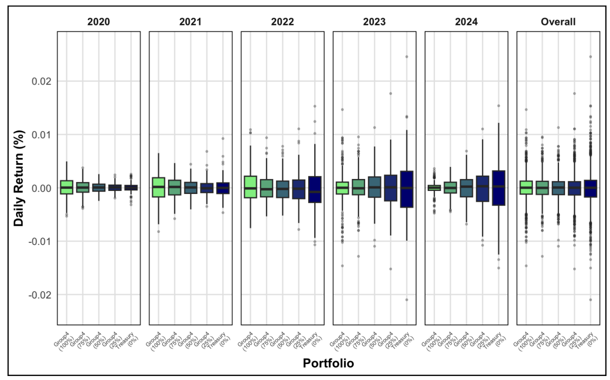
(a) Hybrid Daily Return Distribution – Group 1



(b) Hybrid Daily Return Distribution – Group 2

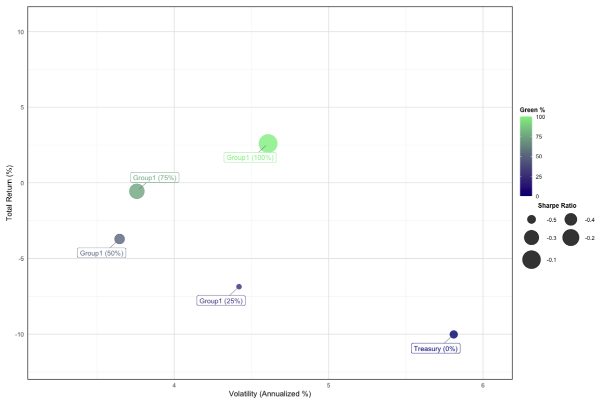


(c) Hybrid Daily Return Distribution – Group 3



(d) Hybrid Daily Return Distribution – Group 4

Figure 14: Hybrid daily returns across duration-based screened portfolios and Treasury (2020–2024).



(a) Hybrid portfolio performance for Group 1 under different green allocations.

(b) Hybrid portfolio performance for Group 2 under different green allocations.

(c) Hybrid portfolio performance for Group 3 under different green allocations.

(d) Hybrid portfolio performance for Group 4 under different green allocations.

Figure 15: Comparative duration-based hybrid portfolio risk–return scatter plots for Groups 1–4, showing total return, annualised volatility, Sharpe magnitude (bubble size), and green-share intensity (colour scale). Bubble size represents Sharpe ratio, with larger bubbles indicating superior risk-adjusted returns. Size is linearly scaled to enable visual comparison of portfolio efficiency across different risk-return profiles.