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Research article

Performance and challenges of net-zero strategies in the context of the EU regulation

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Abstract: In this paper, we present a comprehensive comparative analysis of portfolio construction techniques in the context of decarbonization and the pursuit of net-zero objectives aligned with the 2015 Paris Agreement. We examined strategies qualifying as Article 9 funds under EU regulations, focusing on carbon emission reduction objectives, including screening and tracking-error minimization methods. Our findings indicate that all approaches would have achieved the targeted emission reductions over the 10-year period (2012–2021) analyzed. However, the method of decarbonization significantly affected ex-post tracking error, with the more ambitious Paris-Aligned Benchmark requiring a substantial deviation from the business-as-usual benchmark. Moreover, the tracking-error minimization approach entailed considerable reallocation of individual securities, potentially leading to possibly undesirable idiosyncratic exposures.

Keywords: Net-zero investment; portfolio carbon footprint; climate change; EU regulation; article 9 funds

JEL Codes: G11

1. Introduction

In recent years, aligning investment practices with sustainable objectives has gained considerable attention, particularly in relation to carbon emission reductions. The 2015 Paris Agreement marked a pivotal moment in international climate action, setting ambitious carbon neutrality goals (Net Zero Targets) aimed at limiting global temperature rise to well below 2°C above pre-industrial levels, with further efforts to limit the increase to 1.5°C. Following these initial efforts by governments and major actors to coordinate climate mitigation actions, the carbon neutrality objective has now been embraced by many stakeholders, including companies, asset owners, asset managers, insurers, and banks. The urgent need to address climate change has led to a paradigm shift in investment strategies. As global pressure increases to meet the ambitious goals of the Paris Agreement, investors are compelled to align their portfolios with decarbonization and net-zero (NZ) objectives.

In this context, the European Union (EU) introduced a set of regulations under the Sustainable Finance Action Plan (SFAP), which includes the Sustainable Finance Disclosure Regulation (SFDR).[1] The SFDR establishes mandatory ESG disclosure requirements for asset managers, aiming to increase transparency and prevent greenwashing or false sustainability claims. According to the SFDR classification system, investment funds are classified as Article 6, 8, or 9 depending on their sustainability profile. Article 6 funds are required to only disclose how sustainability risks are considered, irrespective of whether ESG factors are promoted. Article 8 (light green) funds promote environmental or social characteristics, or a combination of both, and must ensure good governance practices. Article 9 funds (dark green) must pursue explicit sustainable investment objectives (environmental and/or social) or carbon emission reduction objectives, in addition to maintaining good governance practices.[2]

Investors pursuing NZ goals typically consider Article 9 funds, which explicitly aim to reduce carbon emissions. The SFDR enables these funds to track specially designed benchmarks, called the EU Climate Transition Benchmark (CTB) and the EU Paris-Aligned Benchmark (PAB), which have distinct levels of ambition in terms of emission reductions. The balance between environmental and financial objectives is central to these funds, which must align their investment strategies with specific climate goals while seeking competitive financial returns. CTB and PAB funds generally invest in companies that are transitioning toward lower carbon emissions or are already aligned with low-carbon pathways. This focus on climate goals can lead these funds to prioritize investments in certain activities while excluding others, potentially affecting their market exposure and reducing diversification. Furthermore, investors in CTB and PAB funds also seek financial returns. The performance of these funds can be impacted by volatility in the sectors they invest in, such as renewable energy, that may have different risk-return profiles compared to more traditional investments. Investing in transitioning firms also entails risk: If these firms fail to deliver on emission targets or adapt to regulatory and market shifts, performance may suffer. These risks must be carefully managed to meet both climate and financial objectives.

In this paper, we examine portfolio construction techniques aligned with SFDR Article 9, each representing a unique approach to sustainable investing: Exclusion strategies, sectoral best-in-class selection, and tracking-error minimization (with or without sectoral constraints). Each approach has distinct underpinnings, which in turn affect portfolio composition and risk-return profiles. By comparing these techniques, we aim to explore the interactions between portfolio construction methodology, regulation, and the pursuit of decarbonization objectives.

To decarbonize a portfolio so that its carbon footprint is compatible with a 1.5°C temperature

[1]More broadly, the SFAP outlines a number of legislative initiatives, including an EU classification system/taxonomy to determine whether an economic activity is sustainable (Taxonomy Regulation), disclosure requirements for various financial market participants (the Regulation (EU) 2019/2088, 2019, on sustainability-related disclosures in the financial services sector, SFDR), and new measures regarding investment benchmarks (Low Carbon Benchmarks Regulation). The European Commission set up a Technical Expert Group on Sustainable Finance (TEG) to assist in developing some of these initiatives.

[2]While our analysis focuses on the EU regulatory context and on European markets, the decarbonization mechanisms discussed here are not specific to the region. Similar benchmark-aligned strategies could be adapted to other jurisdictions, making our approach relevant for comparative analyses in other regions. However, regulatory definitions, data coverage, and investor mandates vary across geographies, which justifies our focus on the European case.

increase above pre-industrial levels, the most direct approach is to exclude high-emitting firms to achieve the desired decarbonization trajectory. The exclusion approach is, in principle, very effective because the distribution of corporate carbon emissions is extremely right-skewed. Specifically, we build a decarbonized portfolio by excluding firms based on their carbon intensity, which measures the amount of carbon emitted per million dollars of revenue. This approach enables us to identify the highest-emitting firms relative to their size. The exclusion threshold is chosen so that the strategy aligns with SFDR Article 9. A drawback of this pure exclusion approach is that the excluded firms often belong to the same energy-intensive sectors (utilities, energy, and materials). For an otherwise passive investor, this approach introduces significant sectoral biases that may be considered undesirable from a diversification perspective. In fact, the EU Technical Expert Group (TEG) stated in 2019 that a pure exclusion approach would not be acceptable, as it results in the underweighting of only high-intensity sectors, thereby leading to divestment from sectors that are key to the energy transition.[3]

To address this issue and substantially reduce the portfolio's carbon footprint, we also consider a sector-neutral best-in-class approach. Similar to the exclusion approach, we exclude firms with the highest carbon intensity but then reinvest the proceeds of the exclusion within the same sector as the excluded firms. In doing so, we preserve the sectoral exposures of the BAU benchmark. We demonstrate that this approach is both effective and easy to implement. However, a limitation of this method is that it does not explicitly account for deviations from the benchmark and the potential impact on tracking error.

As a result, we also consider a third approach to decarbonizing a portfolio, which involves minimizing the tracking error of the portfolio relative to the BAU benchmark. This optimization technique selects portfolio weights by minimizing the standard deviation of past portfolio returns relative to benchmark returns (i.e., tracking error) subject to a carbon reduction constraint. A possible drawback of this approach is that it does not necessarily exclude the most emitting firms or favor companies that play a major role in the transition to a low-carbon economy. As with the screening approaches, this strategy can be implemented with or without sectoral constraints.

We implement these exclusion, best-in-class, and tracking-error minimization strategies dynamically to target decarbonized CTB and PAB portfolios over a 10-year horizon. The portfolio performance from 2012 to 2021 shows that NZ portfolios closely track the performance of their BAU benchmark, despite their substantially lower financed emissions, supporting previous analyses (Bolton et al., 2022, and Jondeau et al., 2025). One implication of implementing the NZ strategy is the extent of tracking error relative to the BAU benchmark. The less ambitious CTB can be implemented with minimal tracking error cost. In contrast, the more ambitious PAB requires a significant departure from the BAU benchmark, even when sectoral exposures are maintained. This higher tracking error is expected, as the carbon intensity is reduced by almost 80% over the 10-year period. However, this risk must be considered in the fund's strategy. Our investigation also reveals another important implication, the recomposition effect, which has significant consequences for investors seeking to balance sustainability objectives with financial performance.

This paper makes three key contributions to the growing literature on sustainable finance and net-

[3]According to the EU TEG, "Achieving minimum requirements set on carbon intensity at index level could be possible by simply divesting from GHG-intensive sectors and reallocating to sectors with very little GHG intensities. As one of the key objectives of EU CTBs and EU PABs is to shift capital from GHG-intensive assets towards solutions necessary to the energy transition, the weighting schemes of these benchmarks should not allow for a simple divestment from sectors key to this transition. In other words, sectors with marginal impacts on climate change and its mitigation should not be overrepresented in EU CTBs and EU PABs compared to their underlying investment universes" (TEG, 2019, page 49).

zero investment strategies. First, we provide a comprehensive, side-by-side analysis of three portfolio construction methods (exclusion, sectoral best-in-class, and tracking-error minimization), implemented dynamically and evaluated out-of-sample over a ten-year period. To our knowledge, we are the first to evaluate these strategies under the regulatory requirements of SFDR Article 9(3), including benchmark-alignment thresholds and exclusion rules. Second, we offer a novel empirical decomposition of portfolio carbon reductions, isolating the respective roles of firm decarbonization, reallocation effects, and regulatory exclusions. This enables us to identify when and how different strategies meet the NZ objective. Third, we provide policy insights into how regulatory design, especially regarding exclusions and benchmark constraints, shapes portfolio risk and sustainability outcomes. Our findings are particularly relevant in light of the ongoing reforms of the SFDR and the possible shift toward sustainability/transition product categories.

Our analysis is grounded in the European equity market and focuses exclusively on the environmental pillar of ESG investing, as defined by the Article 9(3) objective. Yet, the portfolio construction strategies we explore are broadly applicable to other developed markets and could be adapted to a global or multi-regional context. In addition, incorporating social and governance dimensions, particularly where they may interact with or conflict with decarbonization goals, would enable a more comprehensive assessment of sustainable investing strategies.[4] Both extensions would contribute to a deeper understanding of the benefits and challenges of NZ strategies.

1.1. Literature review

In this section, we group key contributions into four major themes that frame our approach: The theoretical foundations of green preferences and risk pricing; empirical evidence on portfolio performance and emission outcomes; the development of NZ investment strategies; and the influence of regulatory frameworks such as the SFDR.

To achieve an NZ objective, a fund manager must significantly reallocate their portfolio, which typically implies a departure from the portfolio benchmark. Our paper is therefore related to the debate on the relative environmental and financial performance of divestment strategies used by green investors. Several researchers have investigated the consequences of introducing environmental objectives into the investment process from a theoretical perspective, notably Pedersen et al. (2021), Pastor et al. (2021, 2022), and Broccardo et al. (2022). In equilibrium, green assets should offer lower expected returns for two complementary reasons. First, these assets serve as a hedge against climate risk. Second, sustainable investors have a preference for green assets. Therefore, investors are willing to pay a premium to hold green assets, thereby reducing their future returns.

However, as argued by Pastor et al. (2021), the shift in demand toward green assets may generate higher realized returns. This theoretical paradox is confirmed empirically by Rohleder et al. (2022), who find that the initial reallocation of capital toward environmentally friendly firms can lead to short-term market outperformance by low-carbon companies. Over time, as portfolios are rebalanced, this valuation effect diminishes. Moreover, in the long term, the energy transition could lead to fundamental changes in the operations of high-carbon firms, either through a shift toward green energy or through regulatory constraints that result in stranded assets. In the context of the transition to a low-carbon economy, it is not clear that brown assets will benefit from higher expected returns. This paradox, where brown stocks command high expected returns but green investors enjoy higher realized returns, is also analyzed in

[4] Industry indexes designed to track an NZ strategy often include ESG filters.

Cheng et al. (2023) within an equilibrium framework. They demonstrate that an NZ strategy can exert sufficient negative price pressure on brown firms to offset the higher expected returns paid by these firms, resulting in higher ex-post performance for green investors.

These seemingly conflicting mechanisms, driven by transitional shifts in investor preferences, may help explain the mixed empirical evidence on the financial consequences of decarbonization. Building on early work by Hong and Kacperczyk (2009), studies such as Garvey et al. (2018) and In et al. (2019) show that strategies favoring carbon-efficient firms are associated with stronger profitability and positive stock returns. Contradicting these findings, Görgen et al. (2020) demonstrate that stocks are positively influenced by a carbon risk factor, implying that brown firms may earn higher returns. This is further supported by Bolton and Kacperczyk (2021), who find that investors demand compensation for exposure to carbon emission risks. Eskildsen et al. (2024) further documented a negative 'greenium,' measured across several ESG metrics and based on forward-looking expected returns.

Several researchers have analyzed the financial and non-financial implications of NZ investment strategies. Palazzolo et al. (2020) examined strategies that significantly reduce a portfolio's carbon footprint and potentially achieve NZ alignment. They highlight that reducing exposure to high-emitting firms can lead to substantial carbon reductions, but achieving more ambitious targets may require shorting high-emitting companies or investing in carbon offsets and emission permits. Le Guenedal and Roncalli (2022) highlight that including scope 3 emissions in the construction of an NZ portfolio increases tracking error and makes the decarbonization process more complex. Barahhou et al. (2022) identified several risks associated with NZ strategies, including high tracking errors relative to a BAU benchmark, diversification risk, and the challenge of designing an NZ strategy that integrates both decarbonization and transition dimensions.

In contrast, Bolton et al. (2022) considered an NZ strategy that minimizes the tracking error of the NZ portfolio relative to the BAU benchmark while reducing the portfolio's carbon footprint by 10% annually. They demonstrated that an approximate NZ portfolio can be constructed with minimal tracking error because high-emitting firms represent a small portion of the overall benchmark. This result is obtained by accepting relatively large weights in certain individual stocks. Jondeau et al. (2025) showed that even a best-in-class strategy, which maintains sectoral and regional exposures aligned with the benchmark, can meet NZ objectives at minimal cost. The resulting tracking error is also limited, due to the reduction of firms' emissions over time. Notably, this strategy achieves not only the targeted carbon reduction but also maintains a risk-adjusted performance comparable to that of the benchmark. Overall, these findings suggest that substantial decarbonization can be achieved at low financial cost for two main reasons: The skewed distribution of corporate emissions and the decreasing emission trend at the firm level. Cenedese et al. (2023) go further by proposing a measure of carbon-transition risk for companies based on NZ portfolios. They introduce the Distance-to-Exit (DTE) metric, defined as the number of years until a company is excluded from an NZ portfolio. They find that firms with high DTE values tend to exhibit higher valuation ratios but lower expected returns, indicating that DTE effectively captures carbon-transition risk.

Most of these papers have highlighted the tension between ambitious decarbonization goals and financial constraints such as tracking error, sector biases, and real-world implementability. We directly address these concerns by conducting a systematic and comparative analysis of three NZ portfolio strategies, the exclusion-based, sectoral best-in-class, and tracking-error minimization strategies, explicitly calibrated to the EU regulatory context (SFDR Article 9(3), CTB, and PAB frameworks). We implement these strategies dynamically over a full decade of data and propose a novel decomposition of portfolio-level carbon reduction, which quantifies the role of firm-level decarbonization versus portfolio reallocation and exclusions. This enables us to assess not only the feasibility of NZ implementation but also the real drivers of emission reduction, which is often left unexamined in the literature.

Finally, there has been growing interest in how regulation influences NZ strategies. The SFDR and related EU initiatives have led to new classifications of sustainable funds and increased disclosure requirements. Becker et al. (2022) analyzed the impact of sustainability labels on fund inflows, while Cremasco and Boni (2022) explored the incentives that drive fund managers to align their strategies with either financial or sustainability objectives. Scheitza and Busch (2023) compared ESG-related and impact-oriented funds in terms of structure and performance characteristics. Together, these studies provide the regulatory and institutional context for our analysis of Article 9 funds and their alignment with the CTB and PAB benchmarks defined under the EU Sustainable Finance Action Plan.

The remainder of the paper is organized as follows. In Section 2, we provide an overview of EU regulation and the development of the green fund market in the EU, describe the dataset used in the empirical analysis, and outline the construction of decarbonized portfolios based on four investment strategies: Exclusion, best-in-class screening, and minimizing tracking error with and without sectoral constraints. In Section 3, we present and discuss the results. In Section 4, we summarize key findings and implications and conclude the paper.

2. Materials and method

2.1. EU regulation

The EU has established a comprehensive regulatory framework for sustainable finance. This framework includes the EU taxonomy, which classifies sustainable economic activities; the Corporate Sustainability Reporting Directive (CSRD), which defines and standardizes firms' ESG disclosures; and the Sustainable Finance Disclosures Regulation (SFDR), which aims to improve transparency in sustainable investment. The objectives of the SFDR are to channel capital toward sustainable products and securities while limiting greenwashing.

The provisions of the SFDR became applicable in March 2021. On April 6, 2022, the European Commission adopted new rules (Commission Delegated Regulation (EU) 2022/1288, 2022), which include more precise technical standards for disclosure requirements and came into force on January 1, 2023. On October 31, 2022, the Commission Delegated Regulation (EU) 2023/363 (2022), which amended and corrected aspects of the previous regulatory standards, was adopted and became applicable on February 20, 2023. Although the SFDR Delegated Regulation has only recently entered into force, the European Commission has already mandated the European Supervisory Authorities (ESAs) to assess and revise the rules laid down in the SFDR Delegated Regulation.[5] They launched two consultations on the implementation of the SFDR: A public consultation and a targeted consultation, which ran from September 14, 2023, to December 22, 2023. A summary report of both consultations was published in May 2024 (European Commission, 2023). In June 2024, the ESAs published a joint opinion on the assessment of the SFDR (JCESA, 2024b), proposing a series of changes to the current SFDR framework and recommending several revisions to enhance coherence and effectiveness in the sustainable finance framework.

[5]The ESAs include the European Banking Authority (EBA), the European Insurance and Occupational Pensions Authority (EIOPA), and the European Securities and Markets Authority (ESMA).

In this section, we briefly present the EU's approach to categorizing sustainable investment, with a focus on how this regulation defines NZ investment strategies, as illustrated in Figure 1. We also provide updated information about the market for NZ funds in the EU.

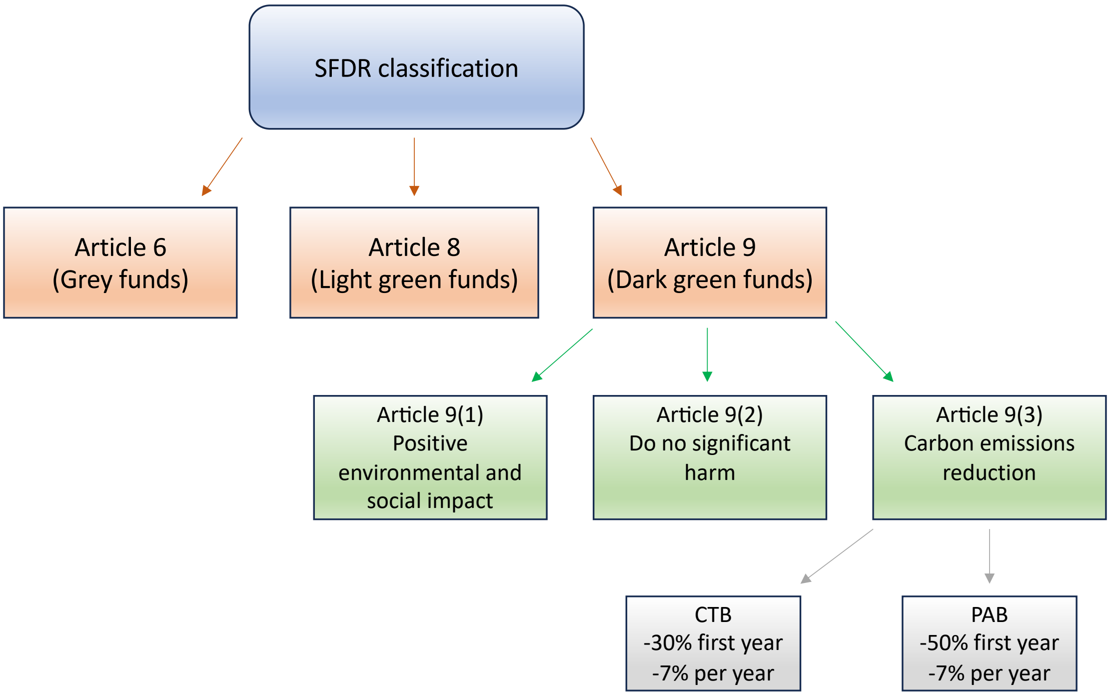


Figure 1. Structure of the SFDR classification.

2.1.1. SFDR fund classification

The SFDR categorizes funds into three types based on Articles 6, 8, and 9. This classification enhances market transparency and enables investors to make more informed choices based on each fund's sustainability profile. This is part of the EU's broader strategy to embed sustainability considerations into the financial sector and promote sustainable investment. The three categories are defined as follows:

- Article 6 funds (Grey funds) are standard funds that do not integrate sustainability risks into their investment decisions or objectives. They constitute the baseline category and are required to only disclose why sustainability risks are not relevant or how these risks are not expected to impact returns. These funds do not focus on sustainability but must communicate their stance on sustainability risks.
- Article 8 funds (Light Green funds) promote environmental or social characteristics but do not have them as their core objective. These funds must ensure that investee companies follow good governance practices. They are more sustainability-focused than Article 6 funds but do not make sustainable investment their primary objective.
- Article 9 funds (Dark Green funds) have sustainable investment as their core objective.[6] These funds aim to achieve a measurable, positive social or environmental impact alongside financial

[6]According to the Joint Committee of the European Supervisory Authorities, to qualify as 'sustainable investment' under Article

returns. Article 9 funds have the highest standards for sustainability and must disclose in detail how their objectives are achieved.

2.1.2. Subcategories of Article 9 funds

Article 9 funds are further divided into three subsections, each reflecting a specific type of sustainable investment strategy:

- Article 9(1) funds aim to invest in activities that directly contribute to environmental or social objectives, as defined by the EU taxonomy. These funds must have a clear and dedicated sustainability goal, and their investment decisions are guided by the pursuit of measurable environmental or social outcomes.
- Article 9(2) funds also aim to ensure that the companies they invest in 'do not significantly harm' environmental or social objectives. This approach requires comprehensive analysis of potential investments to confirm their alignment with sustainability standards.
- Article 9(3) funds target carbon emission reduction, aligning with the objectives of the Paris Agreement. These funds focus on investments that contribute to climate change mitigation and adaptation and are expected to align their portfolios with the transition to a low-carbon, climate-resilient economy. They typically invest in companies that directly and measurably reduce GHG emissions.

This classification enables investors to distinguish funds based on their level of sustainability ambition, from broad ESG alignment to targeted emission reduction, thereby facilitating investment decisions aligned with individual sustainability preferences.

2.1.3. Benchmarks under Article 9(3)

Under Article 9(3), funds must demonstrate alignment with the goals of the Paris Agreement. The SFDR provides the minimum requirements for defining two benchmarks compliant with Article 9(3): The Climate Transition Benchmark (CTB) and the Paris-Aligned Benchmark (PAB). Both aim to facilitate portfolio decarbonization, but differ in terms of ambition and exclusions.

CTBs are designed to support a gradual transition toward a low-carbon economy. They are suitable for investors who want to contribute to climate change mitigation while considering a broader investment universe. CTBs must meet the following criteria: (1) Exclude sin stocks;[7] (2) reduce index-level carbon intensity by at least 30% relative to the parent index in the base year; and (3) achieve an annual reduction in index-level carbon intensity of at least 7% relative to the previous year's index. Importantly, CTBs enable continued investment in high-emitting firms that are actively transitioning to lower emissions.

PABs are more stringent, designed for portfolios that are more aggressively aligned with the 1.5°C objective of the Paris Agreement. In addition to excluding sin stocks, PABs exclude fossil fuel-intensive companies based on the following criteria: (1) Companies with 1% or more of their revenue from coal and lignite-related activities; (2) companies with 10% or more of their revenue from oil exploration, extraction, distribution, or refining; (3) companies with 50% or more of their revenue from

2(17) SFDR, a financial product must (1) be invested in economic activities that contribute to an environmental or social objective, (2) not significantly harm any of those objectives; and (3) ensure that the invested companies follow good governance practices, including management structures, employee relations, remuneration, and tax compliance (JCESA, 2024a).

[7]Sin stocks include companies involved in activities related to controversial weapons (as referred to in international treaties and conventions, UN principles, and national legislation), tobacco cultivation and production, and firms in violation of the UN Global Compact (UNGC) principles or the Organization for Economic Co-operation and Development (OECD) Guidelines for Multinational Enterprises.

gas exploration, extraction, manufacturing, or distribution; and (4) companies with 50% or more of their revenue from electricity generation whose GHG intensity exceeds 100g CO_2e/kWh.

PABs must also reduce the index-level carbon intensity by at least 50% relative to the parent index in the base year and continue reducing carbon intensity by at least 7% per year thereafter. Investments under PABs are more selective, focusing on companies that are already demonstrating strong climate performance.

In April 2023, the European Commission stated that funds with a carbon emission reduction objective under Article 9(3) may be actively managed and are not required to passively track an EU PAB or CTB. However, such actively managed funds must comply with the sustainable investments test under Article 2(17) of the SFDR (see footnote 6). By contrast, Article 9(3) funds that passively track an EU PAB or CTB are deemed compliant with the Article 2(17) and are not subject to the additional sustainable investment test.[8]

2.1.4. The Market for green funds in the EU

Statistics on funds classified under the SFDR can be obtained from the Morningstar database. As of March 2024, the breakdown of the number of funds is 51.6%, 44.3%, and 4.1% for Article 6, Article 8, and Article 9 funds, respectively. In terms of assets under management, the breakdown is 41.1%, 55.5%, and 3.4%, respectively. Interestingly, these figures indicate that nearly 60% of fund assets in the EU are managed with some level of ESG integration. They also reveal that Article 9 funds constitute a niche segment for investors seeking particularly stringent sustainability mandates. As of March 2024, among the 1,024 funds classified as Article 9 funds with a European ESG template, 292 funds (approximately 29%) reported having a carbon-reduction objective.

Article 9 funds were significantly affected by the so-called ‘Great Reclassification’. During the fourth quarter of 2022, over 70% of ETFs that were classified as Article 9 under SFDR were voluntarily downgraded to Article 8 by their asset managers. The main reason for this widespread downgrading was the uncertainty surrounding the stringency of the Article 2(17) sustainable investment test. Because this provision was interpreted to require 100% of securities held by an Article 9 fund qualify as ‘sustainable’, most PAB and CTB strategies would no longer meet the criteria. Given the lack of explicit sustainability standards and the difficulty of meeting the SFDR’s requirements, many asset managers opted for the more conservative and flexible classification under Article 8. This reclassification episode raised concerns about the feasibility and merits of a rule-based approach for investors seeking exposure to sustainable investments. It also highlighted the complexities and challenges in navigating the evolving ESG regulatory framework in the EU.

The reclassification had a significant impact on the market share of passive funds within the Article 9 category. Morningstar reported that the market share of passive Article 9 funds decreased from 24.1% to just 5.1% in the last quarter of 2022. Most of these downgrades affected equity strategies, with a substantial portion of these assets allocated to PABs and CTBs. In response, the European Commission clarified that both PAB and CTB benchmarks are deemed to provide ‘sustainable investments’. This clarification opened the possibility for funds that were downgraded from Article 9 to Article 8 to be re-upgraded.

[8] Several index providers, such as S&P Global, MSCI, FTSE, STOXX, and Morningstar, offer indices that meet the criteria for compliance with CTB and PAB.

2.1.5. Toward a new disclosure framework?

Although the SFDR was initially designed to increase transparency regarding sustainability, in practice, the disclosure frameworks under Article 8 and Article 9 have often been treated more as product labels, as observed by the European Commission (2023) and the JCESA (2024b). This labeling approach contributed to confusion and increased the risks of greenwashing and mis-selling, which culminated in the Great Reclassification. In its September 2023 consultation, the European Commission proposed two alternatives for reforming the SFDR framework: (1) Clarifying the distinction between Article 8 and Article 9 products, or (2) creating new product categories based on investment strategies.

According to the Summary Report of the Open and Targeted Consultations on the SFDR assessment, there is no clear preference between the two proposals. However, in their joint opinion issued on June 18, 2024, the ESAs highlighted the limitations of the current framework, noting that investors find SFDR disclosures confusing and difficult to understand. To address this, the ESAs advocate for the second option, which involves replacing the current Article 8 and Article 9 disclosure system with distinct product categories. They argued that such a change would improve investor understanding.

The ESAs also noted that the Article 8 category of financial products is too broad. The "promotion of environmental or social characteristics" mentioned in this Article allows for broad interpretation, making it challenging for investors to accurately assess the actual sustainability profile of these products. The European Commission acknowledged this broad scope in a July 2021 interpretative Q&A.

Disclosures under Article 9 have also faced challenges, despite their association with sustainable investments as defined in Article 2(17) of the SFDR. In practice, the broad and flexible definition of sustainable investment has led to limited comparability across Article 9 products, as product manufacturers have significant discretion in defining these investments.

The ESAs recommend creating two new product categories, 'sustainability' and 'transition' with clear and objective criteria or thresholds. The goal is to maintain category integrity and build investor trust. The 'sustainability' category would include products that invest in activities and assets already aligned with environmental or social objectives, such as those aligned with the EU Taxonomy for environmentally sustainable products. The 'transition' category would include products investing in activities or assets not yet sustainable but expected to become so, following a clear pathway aligned with EU and global environmental and social goals.

The two-category approach proposed by the ESAs is simpler compared to the four labels being introduced under the United Kingdom's Sustainability Disclosure Requirements (SDR) and investment labeling regime. However, these categories are suggested as a preliminary framework, with the European Commission having the option to develop more detailed categories if it proceeds with this proposal.

Notably, none of this discussion suggests, either explicitly or implicitly, that the definition of NZ strategies would be affected by a change in disclosure regulations. It is very likely that most of the rules governing the implementation of an NZ strategy are expected to remain consistent with those described in the following sections.

2.2. Data

To investigate the impact of the SFDR regulation on the construction of NZ strategies, we consider a portfolio that complies with the requirements outlined in Article 9(3).[9] Following the logic of Article 9(3), we construct both a CTB and a PAB based on a parent index. For the parent index, we use the MSCI Europe Index, which selects firms from developed European countries. This widely used benchmark provides a reference for assessing investment strategies in terms of financial performance and carbon metrics. Since carbon emission data are unavailable for a small number of firms in the index, we define a BAU benchmark, which we use as the parent index, consisting only of firms for which carbon data are available. On average, 21 companies (approximately 2% of the market value of the index) are excluded due to missing data from the matching of MSCI and Trucost databases over the period 2011–2021.[10]

We use annual carbon emission data for Scopes 1 and 2 from the Trucost GHG database, with data available from 2005 to 2021 in our latest update.[11] Scope 1 refers to direct emissions generated from burning fossil fuels and production processes owned or controlled by a company. Scope 2 includes first-tier indirect emissions from the consumption of purchased electricity, heat, or steam by a company.[12]

Figure 2 displays the histograms of Scopes 1 and 2 carbon emissions and intensity of the benchmark constituents in 2021, in Panels A and B, respectively. Carbon emissions are measured in metric tons of CO_2 equivalent (tCO_2e) and carbon intensity is measured in tCO_2e per mln EUR revenue. Both plots are in logarithmic scale to account for the extreme right-tailed asymmetry observed in the data: A small number of firms emit disproportionately large amounts of carbon. The top 1% of firms (with carbon intensity above $3,541.4$ tCO_2e per mln EUR) account for 27.4% of the benchmark's total carbon intensity in 2021. The top 10% and 25% of firms contribute 71.4% and 90.2%, respectively, to total carbon intensity.

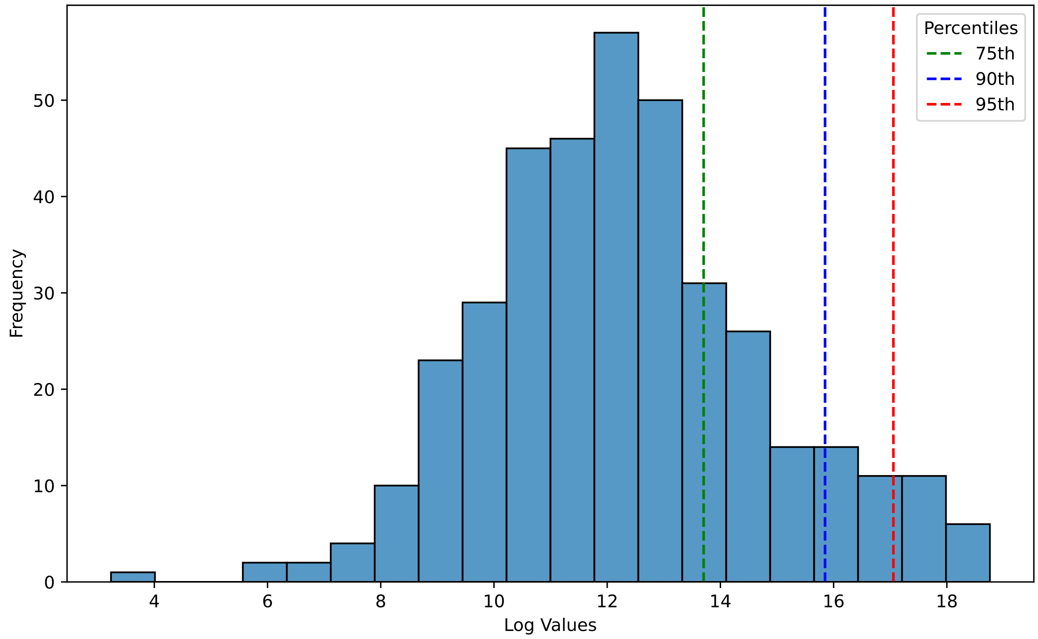
Table 1 reports further descriptive statistics at the sectoral level. First, the contribution of each sector to overall emissions shows that three sectors (materials, utilities, and energy) are the dominant contributors to carbon emissions among the 11-sector GICS nomenclature. These sectors represent 42.2%, 29.1%, and 15.6% of total emissions, respectively, as also shown in Figure 3 (Panel A). Together, they account for 86.8% of total carbon emissions in 2021, despite comprising only 18.9% of the firms in the benchmark. In contrast, the least carbon-intensive sectors (real estate, information technology, and financials) account for just 0.9% of total carbon emissions while representing 26.7% of the firms in the benchmark. Second, when emissions are normalized by firms' revenues, the materials, utilities, and energy sectors are the most carbon-intensive sectors, as shown in Table 1 and Figure 3 (Panel B).

[9] An alternative approach would involve analyzing the financial and non-financial performance of listed funds qualifying as Article 9(3). However, this approach presents challenges, as most CTB and PAB indices or ETFs include additional restrictions beyond those imposed by the SFDR, such as a maximum exposure to individual stocks and minimum ESG scores. This would prevent us from accurately assessing the characteristics of funds based on the SFDR alone.

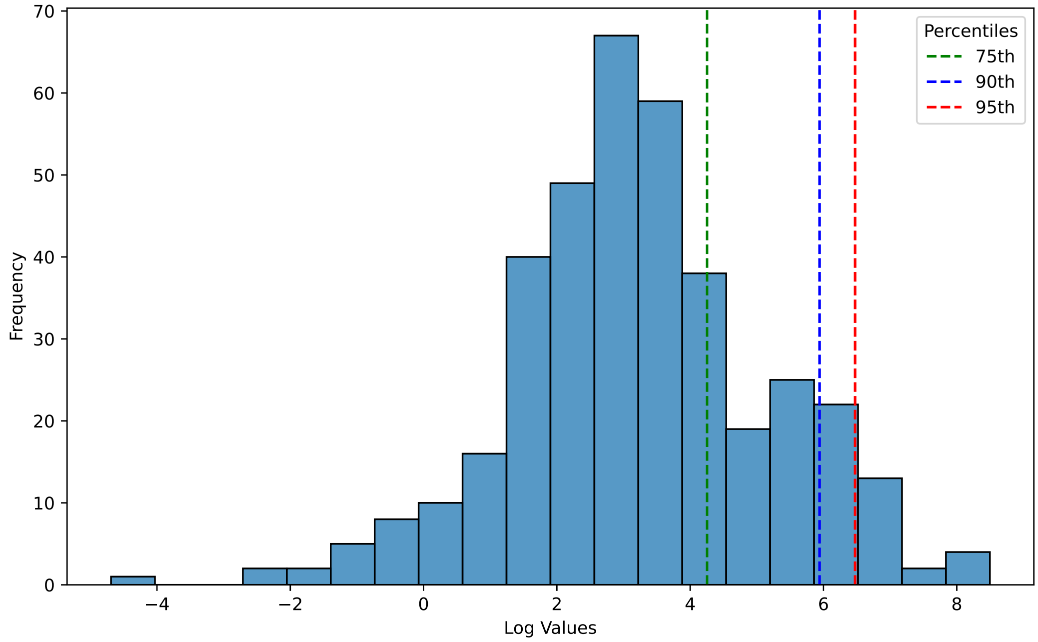
[10] The total number of companies in the index with complete data is 377 in 2011 and 382 in 2021.

[11] We note that carbon emission data typically become available with a lag of 12 to 18 months. At the time of writing, firm-level carbon data for 2022 or later were not fully available.

[12] Scope 3 upstream relates to other indirect emissions, such as those from the extraction and production of purchased materials and fuels, transport-related activities in vehicles not owned or controlled by the reporting entity, and electricity-related activities not covered in Scope 2. While Scope 3 upstream emissions can be substantial for certain sectors, such as automotive and fossil fuel companies, and can account for a large portion of a company's carbon emissions, data coverage remains limited. We report the main results based on Scopes 1 and 2 and discuss the impact of including Scope 3 upstream emissions in Section 3.4.

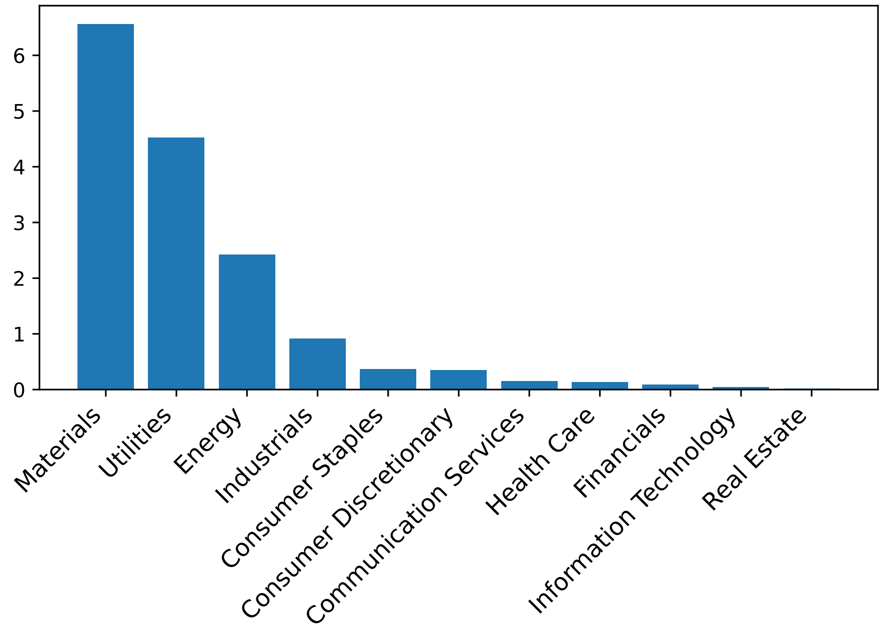


Panel A: Carbon emissions (tCO_2e).

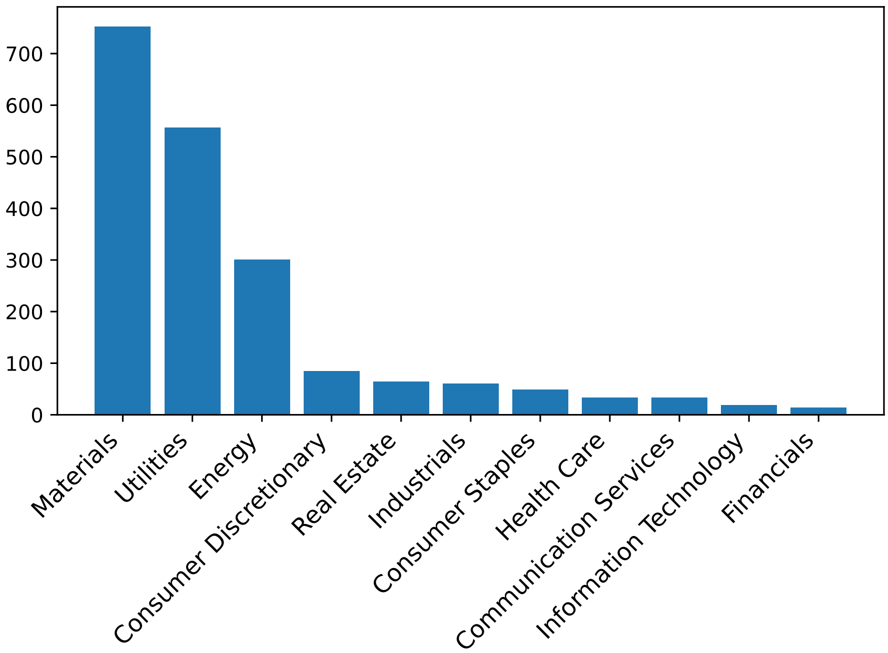


Panel B: Carbon intensity (tCO_2e/mln EUR revenue).

Figure 2. Histograms of the Carbon emissions and intensity (as of 2021). (Note: This figure represents the histograms of the Scopes 1 and 2 carbon emissions and intensity of firms in the MSCI Europe in 2021. Carbon emissions are measured in tCO_2e. Carbon intensity is measured in tCO_2e/mln EUR revenue. The histogram is in log scale. The figure also displays the 75%, 90%, and 99% thresholds.)



Panel A: Carbon emissions (million tCO_2e).



Panel B: Carbon intensity (tCO_2e/mln EUR revenue).

Figure 3. Carbon emissions and intensity by Sector (as of 2021).(Note: Note: This figure represents the Scopes 1 and 2 carbon emissions and intensity of the sectors in the MSCI Europe in 2021. Carbon emissions are measured in million tCO_2e. Carbon intensity is measured in tCO_2e/mln EUR revenue.)

Table 1. Sectoral data as of end of 2021.

Sector	Number of firms	Proportion (in %)	Share (in %)	Carbon emissions	Contribution (in %)	Carbon intensity
Materials	36	9.42	8.05	656.33	42.19	752.86
Utilities	25	6.54	4.54	452.44	29.09	557.11
Energy	11	2.88	4.84	241.95	15.55	300.54
Industrials	69	18.06	15.59	91.66	5.89	60.38
Consumer Staples	35	9.16	12.40	36.52	2.35	48.62
Consumer Discretionary	38	9.95	10.78	34.47	2.22	84.53
Communication Services	28	7.33	3.58	14.62	0.94	33.29
Health Care	38	9.95	14.18	13.58	0.87	33.64
Financials	68	17.80	15.70	8.56	0.55	14.04
Information Technology	22	5.76	9.08	3.90	0.25	18.78
Real Estate	12	3.14	1.24	1.54	0.10	64.15
	382	100.0	100.0	1555.6	100.0	–

Note: Share represents the market value of the sector in percentage of the market value of the BAU benchmark. Carbon emissions are the cumulative emissions of all the firms of a given sector, measured in tCO_2e. Carbon intensity is the weighted average of the carbon intensity of all the firms of a given sector, measured in tCO_2e/mln EUR revenue.

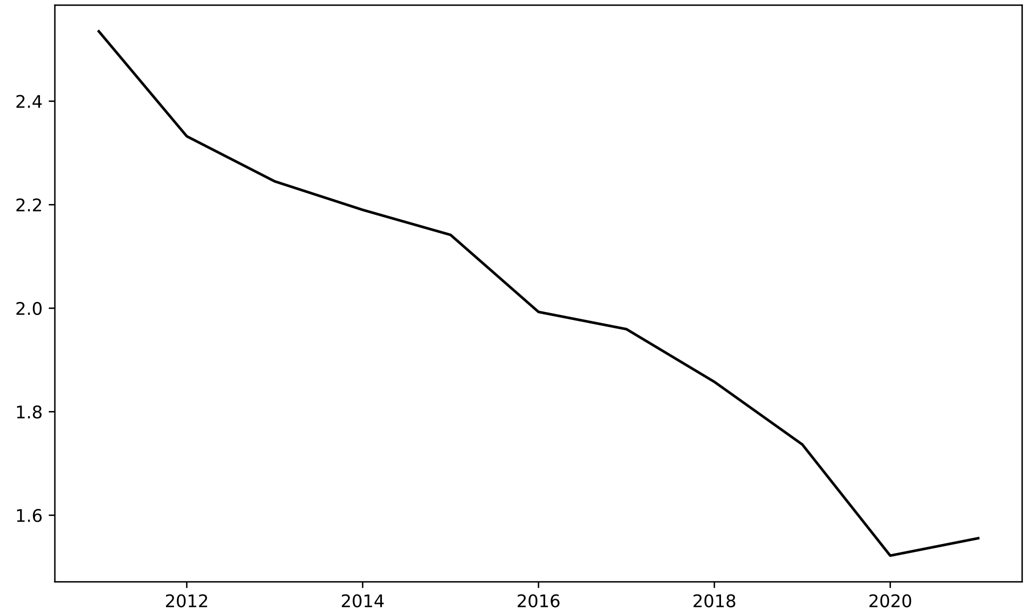
The ten most emitting companies in terms of carbon emissions are ArcelorMittal, Holcim, RWE, Heidelberg Materials (formerly HeidelbergCement), Shell, Fortum, Enel, Uniper, Evraz, and ENI. Together, they represent 49.4% of total carbon emissions, with the top five alone contributing 32.7% of emissions in 2021.[13] All these companies belong to just three sectors: Materials, utilities, and energy. Therefore, a substantial reduction in a portfolio's carbon emissions can be achieved by excluding a small number of high-emitting companies from these three sectors. However, this raises the challenge of reducing emissions while maintaining sectoral exposures similar to the BAU benchmark.

To assess the carbon exposure of a portfolio, we use the weighted-average carbon intensity (WACI), as recommended by the Task Force on Climate-related Financial Disclosures (TCFD, 2017). The (ex-post) WACI of the BAU benchmark is defined in a given year Y as follows (in tCO_2e/mln EUR revenue):

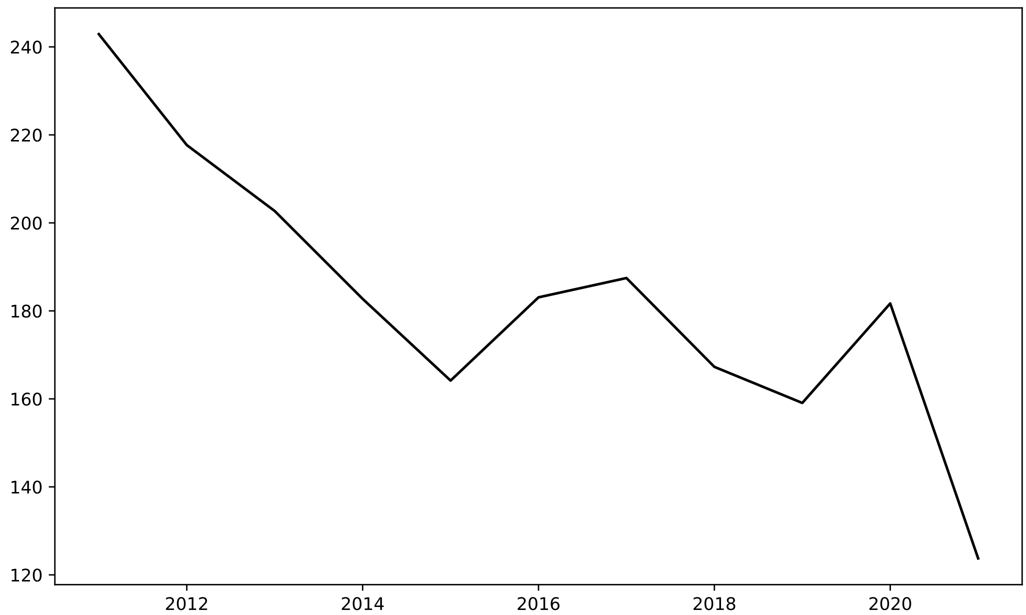
$$WACI_Y^{(b)} = \sum_{i=1}^{N_Y} w_{i,Y-1}^{(b)} CI_{i,Y}, \tag{1}$$

where $CI_{i,Y} = E_{i,Y}/Rev_{i,Y}$ denotes the carbon intensity of firm i, with $E_{i,Y}$ its carbon emissions, $Rev_{i,Y}$ its revenues, $w_{i,Y-1}^{(b)}$ its weight in the benchmark at the end of year $Y-1$, and N_Y the number of companies in the parent index. This metric is referred to as 'ex post' because it is based on the carbon emissions in year Y, which are only known at the end of the year. Accordingly, it is the metric we use to report the carbon performance of a portfolio. In the design of the investment strategy, because investment decisions are made at the end of year $Y-1$ for the upcoming year Y, portfolio weights must be based on 'ex-ante' emissions, i.e., the emissions from year $Y-1$.

[13]Evraz is a U.K.-incorporated steel manufacturing and mining company, partly owned by Russian stockholders. Its listing on the London Stock Exchange was temporarily suspended in March 2022.



Panel A: Carbon emissions (million tCO_2e).



Panel B: Weighted-average carbon intensity (tCO_2e/mln EUR revenue).

Figure 4. Evolution of the benchmark Scopes 1 and 2 Carbon emissions and intensity. (Note: This figure represents the evolution of the Scopes 1 and 2 carbon emissions (Panel A) and WACI (Panel B) of the MSCI Europe benchmark between 2011 and 2021. Carbon emissions are measured in million tCO_2e. Carbon intensity is measured in tCO_2e/mln EUR revenue.)

Figure 4 shows the evolution of carbon emissions and WACI for the BAU benchmark from 2011 to 2021. Over the sample period, total carbon emissions declined steadily with a cumulative reduction of 38.6% over 10 years. Moreover, carbon intensity declined by a total of 49.1%. This trend reflects the broader decarbonization efforts by large, high-emitting firms, which have steadily reduced their emissions over time. The decline in carbon intensity within the benchmark facilitates the task of Article 9 funds aiming to reduce portfolio emissions. If the objective is to reduce the WACI by 63.6% (CTB targets) or 74% (PAB targets) over 10 years, the BAU benchmark already delivers a 49.1% reduction. The remaining 14.5% or 24.9% to be achieved through the fund's active screening and reallocation strategies.

2.3. Methodology

In this section, we describe three portfolio construction methods designed to align with the carbon reduction objectives defined under SFDR Article 9(3). These approaches are grounded in practical considerations faced by sustainable investors. Each method satisfies the required decarbonization trajectory (30% or 50% initial cut and 7% annual reduction), but reflects a different trade-off between environmental ambition, portfolio diversification, and benchmark tracking. Below, we detail the rationale, implementation, and specific constraints of each method.

The documentation published by EU regulators does not prescribe how CTB and PAB indexes should be constructed. Instead, it provides guidelines and constraints (such as minimum required reductions in carbon intensity, sectoral exposures, etc.), while leaving the precise design of investment strategies open to interpretation. We consider two classes of strategies for constructing a climate index benchmark (CTB or PAB): (1) Screening strategies, which include pure exclusion and best-in-class methods; and (2) tracking-error minimization strategies, which reallocate weights while minimizing deviations from the BAU benchmark. In all cases, carbon emissions must be reduced in line with regulatory thresholds, but the selection of stocks to be excluded may vary. Screening methods prioritize excluding firms with the highest carbon intensity. In contrast, tracking-error minimization involves a trade-off between excluding firms that contribute most to the portfolio's carbon intensity and those that contribute most to the tracking error.

2.3.1. Screening methods

Screening methods, which are among the most commonly used decarbonization tools in sustainable investment, directly exclude high-emitting firms from the portfolio. These strategies are easy to implement and transparent, making them attractive to otherwise passive investors and regulators. We examine two screening variants for reinvesting the proceeds from the exclusion of high-emitting firms (see, among others, Jondeau et al., 2025). In the exclusion method, proceeds are reinvested proportionately across all remaining firms according to their weight in the BAU benchmark. In the best-in-class method, proceeds are reinvested in the least carbon-intensive firms within the same sector as those excluded.

We begin by identifying firms with the highest carbon intensities and describing how we construct the climate index (hereafter referred to as the 'portfolio'). The exclusion process is conducted annually using carbon intensity data from the previous year.[14] In this way, a firm excluded in one year may

[14]Emission data for year Y typically become available several months later, often mid-year $Y + 1$. Given the extensive heterogeneity in carbon emissions across firms, we do not expect any major impact on the screening of firms. As emissions tend generally decline over time, ex-post portfolio emissions tend to be lower than ex-ante emissions.

re-enter the portfolio if its emissions fall below the exclusion threshold in subsequent years.

Portfolio weights for year Y are determined at the end of year $Y-1$, which we denote by $w^{(p)}_{Y-1}$, based on the latest available data. The ex-ante WACI of the portfolio is then $EWACI^{(p)}_Y = \sum_{i=1}^{N_Y-1} w^{(p)}_{i,Y-1} CI_{i,Y-1}$, which is based on the last available emissions of year $Y-1$. The evaluation of the carbon performance of the strategy will be based on the ex-post WACI, which corresponds to the WACI of the portfolio for year Y based on the actual emissions in year Y.

For year $Y = 2012$, we determine the list of firms to exclude based on their carbon intensity in 2011 to ensure that the portfolio WACI is reduced by 30% or 50% relative to the BAU benchmark WACI of 2011. Then, each year, the portfolio WACI must be further reduced by 7% relative to the previous year's target. This additional reduction is imposed each year even if the portfolio failed to reduce its ex-post carbon intensity the previous year. The annual emission reduction constraint ensures that portfolio weights selected at the end of year $Y-1$ comply with the regulatory carbon trajectory for year Y. It is expressed as:

$$EWACI^{(p)}_Y \leq WACI^{(target)}_Y \equiv (1-\theta)(1-\xi)^{Y-Y_0-1} WACI^{(b)}_{Y_0}, \qquad Y = 2012, ..., 2021 \tag{2}$$

with $\theta = 30\%$ for CTB or 50% for PAB, $\xi = 7\%$ and $Y_0 = 2011$. In the exclusion method, the proceeds of the exclusion are reinvested in the remaining stocks proportionately to their market value. Therefore, the reinvestment stage has no impact on the final WACI of the portfolio. The weights of the pure exclusion portfolio are constructed as follows. In year Y, the constraint $EWACI^{(p)}_Y \leq WACI^{(target)}_Y$ defines a threshold q_Y for the carbon intensity of firms in the investment universe. All firms with a carbon intensity above q_Y must be excluded to satisfy the constraint (2). Technically, the threshold q_Y is defined such that:

$$\sum_{i=1}^{N_Y-1} w^{(p)}_{i,Y-1}(q_Y) CI_{i,Y-1} = WACI^{(target)}_Y \qquad \text{with} \qquad w^{(p)}_{i,Y-1}(q_Y) = \frac{w^{(b)}_{i,Y-1} 1_{\{CI_{i,Y-1} > q_Y\}}}{\sum_{j=1}^{N_Y-1} w^{(b)}_{j,Y-1} 1_{\{CI_{j,Y-1} > q_Y\}}} \tag{3}$$

In practice, weights $w^{(p)}_{i,Y-1}(q_Y)$ are obtained as follows. We define the list of firms to be excluded as $I_{H,Y} = \{1_{\{CI_{i,Y-1} > q_Y\}}\}_{i=1}^{N_Y-1}$ and the list of firms included in the portfolio as $I_{I,Y} = \{1_{\{CI_{i,Y-1} \leq q_Y\}}\}_{i=1}^{N_Y-1}$ (set of firms complementary to $I_{H,Y}$). The threshold also defines the sum of the market weights of excluded firms as $\sum_{i=1}^{N_Y-1} w^{(b)}_{i,Y-1} 1_{\{CI_{i,Y-1} > q_Y\}}$ and the number of excluded firms as $N_{H,Y} = \sum_{i=1}^{N_Y-1} 1_{\{CI_{i,Y-1} > q_Y\}}$. The proceeds are reallocated proportionately to all stocks remaining in the portfolio. The vector of weights in the pure exclusion portfolio is therefore given by:

$$w^{(p)}_{i,Y-1} = \begin{cases} 0 & \text{for } i \in I_{H,Y} \\ w^{(b)}_{i,Y-1} \left(\frac{1}{\sum_{j \in I_{I,Y}} w^{(b)}_{j,Y-1}} \right) & \text{for } i \in I_{I,Y}. \end{cases}$$

In the best-in-class method, the proceeds of the exclusion of a given firm in a given sector are reinvested in firms with the lowest carbon intensities in the same sector. Therefore, if the market value of firms excluded in sector s represents a fraction $\gamma_Y(s)$ of the market value of the sector, we reinvest the same amount by doubling the weights of the firms with the lowest carbon intensity representing the same fraction $\gamma_Y(s)$ of the sector market value. This reinvestment method is likely to have a limited impact on the WACI of the portfolio because reinvesting in firms with low carbon intensities in high-emitting sectors may contribute to the overall carbon footprint of the portfolio. Thus, the exclusion threshold must take this contribution into account. Weights are obtained as follows.

We denote by S_i the sector of firm i, so $1_{\{S_i=s\}} = 1$ if the firm belongs to sector s and 0 otherwise. We also denote the set of firms in a given sector s by $I_Y(s) = \{1_{\{S_i=s\}}\}_{i=1}^{N_Y-1}$, for any s. For a given exclusion threshold q_Y based on Equation (2), the list of firms to be excluded in a given sector s is defined by $I_{H,Y}(s) = \{1_{\{S_i=s,CI_{i,Y-1}>q_Y\}}\}_{i=1}^{N_Y-1}$, for any s. In this sector, a proportion $\gamma_Y(s) = \sum_{j\in I_{H,Y}(s)} w_{j,Y-1}^{(b)} / \sum_{j\in I_Y(s)} w_{j,Y-1}^{(b)}$ of the market value is excluded. The proceeds are reinvested in the same sector in the set of firms with the lowest carbon intensities with a cumulative market value approximately equal to $\sum_{j\in I_{H,Y}(s)} w_{j,Y-1}^{(b)}$. The set of overweighted firms in sector s is therefore defined as $I_{L,Y}(s) = \{1_{\{S_i=s,CI_{i,Y-1}\leq q_{\gamma_Y(s),Y}\}}\}_{i=1}^{N_Y}$, where $q_{\gamma_Y(s),Y}$ is the carbon intensity threshold corresponding to proportion $\gamma_Y(s)$. The overall set of excluded and overweighted firms are given by $I_{H,Y} = \{I_{H,Y}(s)\}_s$ and $I_{L,Y} = \{I_{L,Y}(s)\}_s$, respectively.

The weights of the best-in-class method are defined as follows:

$$w_{i,Y-1}^{(p)} = \begin{cases} 0 & \text{for } i \in I_{H,Y} \\ w_{i,Y-1}^{(b)} & \text{for } i \in I_{I,Y} \\ w_{i,Y-1}^{(b)}\left(1 + \frac{\sum_{j\in I_{H,Y}(S_i)} w_{j,Y-1}^{(b)}}{\sum_{j\in I_{L,Y}(S_i)} w_{j,Y-1}^{(b)}}\right) & \text{for } i \in I_{L,Y}, \end{cases}$$

with $\sum_{j\in I_{L,Y}(S_i)} w_{j,Y-1}^{(b)} \approx \sum_{j\in I_{H,Y}(S_i)} w_{j,Y-1}^{(b)}$. The term in parentheses in the last equation ensures that the sectoral exposures of the resulting portfolio are exactly the same as the exposures of the BAU benchmark at the time of investment. The overweighting is the same for all low-emitting firms in the same sector ($I_{L,Y}(s)$), although it may be different across sectors. As the WACI of the portfolio depends on the selection of the overweighted firms in each sector, the initial exclusion threshold q_Y is likely insufficient, which calls for an iterative process to select the best-in-class portfolio.[15]

After defining the portfolio weights at the end of year $Y-1$ for the investment in year Y, we compute the ex-post return assuming a buy-and-hold strategy between two rebalancing steps. Ex-post returns in month t of year Y are computed as:

$$R_t^{(p)} = \tilde{w}_{t-1}' R_t, \text{ for } t = 1, ..., 12,$$

where

$$\begin{aligned} \tilde{w}_{i,0} &= w_{i,Y} \\ \tilde{w}_{i,t} &= \tilde{w}_{i,t-1} \frac{1 + R_{i,t}}{1 + R_t^{(p)}} \quad \text{for } t = 1, ..., 11. \end{aligned}$$

Monthly ex-post returns enable us to compute and compare the ex-post performance of the various investment strategies.

In general, the increase in weights of overweighted firms is limited. Most of the time, when excluded firms represent less than 50% of a sector's market value, the weights of overweighted firms are typically doubled. In some extreme cases, the fraction of excluded firms may exceed 50% of the sector's market

[15] In practice, we begin with the exclusion threshold q_Y used in the exclusion approach. If the resulting WACI does not meet the reduction target, we gradually exclude more firms until it does.

value. For instance, in 2021, European utilities above the exclusion threshold of 209.87 tCO_2e/mln EUR revenue represent 3.23% of the portfolio value and 60.6% of the utilities sector's market value. The proceeds of this exclusion are reinvested in the 39.4% least-emitting firms among European utilities. Therefore, the weight of these firms is multiplied by a factor $(1 + 0.394/0.606) = 2.65$.

The best-in-class method aligns with SFDR recommendations to maintain sectoral exposures consistent with the BAU benchmark. The logic behind this recommendation is that excluding all firms in a given sector would raise issues from an economic perspective. In fact, the EU regulation implicitly acknowledges that all oil and gas firms are eventually excluded but requires that exposures in other high-emitting sectors remain the same as in the benchmark. This approach also makes sense from a financial perspective (for diversification purposes) and ensures that the composition of the portfolio is consistent with the economy's transition. However, it could make achieving the portfolio's NZ objective more challenging.

2.3.2. Tracking-error minimization methods

In contrast to screening methods, tracking-error minimization strategies are optimization-based approaches used to achieve climate targets while minimizing deviations from a reference benchmark. This method reflects real-world fund constraints, where investors must balance decarbonization goals with performance expectations and client mandates. By minimizing the tracking error, i.e., the volatility of the return difference between the portfolio and the benchmark, the method helps maintain financial performance while achieving regulatory carbon intensity targets.

We apply the same set of constraints, i.e., reduction of the carbon intensity by 30% or 50% relative to the 2011 WACI of the BAU benchmark in the first period, and by at least 7% per year afterwards. More precisely, the decarbonization process involves reweighting the stocks of carbon-intensive companies in the BAU benchmark, while minimizing the tracking error of the NZ portfolio relative to the BAU benchmark.

The ex-ante tracking error (ETE) is defined as the expected standard deviation of the return difference between the climate index portfolio and the BAU benchmark. The minimization problem is written as follows, for $Y = 2012, ..., 2021$:

$$\begin{aligned} \min_{w^{(p)}_{Y-1}} \quad & ETE^{(p)}_Y = (w^{(p)}_{Y-1} - w^{(b)}_{Y-1})' \Sigma_Y (w^{(p)}_{Y-1} - w^{(b)}_{Y-1}) \\ \text{s.t.} \quad & \sum_{i=1}^{N} w^{(p)}_{i,Y-1} = 1 \\ \text{s.t.} \quad & EWACI^{(p)}_Y \leq (1-\theta)(1-\xi)^{Y-Y_0-1} WACI^{(b)}_{Y_0}, \end{aligned} \tag{4}$$

where Σ_Y is the covariance matrix of returns for Y based on data up to $Y - 1$.

Since this strategy aims to reduce emissions while preserving diversification and benchmark alignment, constructing a stable and realistic covariance matrix is essential. To achieve this, we adopt a multi-factor model widely used in asset management. Given the large number of firms and the limited number of temporal observations, we use a multi-factor model to achieve a well-defined covariance matrix. It is defined as: $\Sigma_Y = \beta_Y \Omega_Y \beta_Y' + \Delta_Y$, where Ω_Y is the covariance matrix of factors, β_Y is the matrix of factor exposures and Δ_Y is the diagonal matrix of idiosyncratic variances. We use the five Fama-French factors for Europe (converted into EUR) to estimate the covariance matrix.[16] These

[16]The five Fama–French factors include the market factor, the small-minus-big (SMB) factor, and the high-minus-low (HML) factor,

factors are used to estimate the factor loadings of each stock, which are then used to construct the covariance matrix.

This factor structure captures systematic risk exposures (market, size, value, operating profitability, and investment) that drive correlations among assets, while isolating idiosyncratic risk. It also enables for more robust covariance estimation when the number of assets is large relative to available return observations, a common challenge in the design of climate-aligned portfolios. Factor models are estimated at the end of every year $Y-1$ using monthly returns over the last 10 years ($Y-10$ to $Y-1$). The covariance matrix of factors is computed using the last 10 years of monthly factor returns, while idiosyncratic variances are computed using monthly residuals from the factor models.

2.3.3. Other constraints

Two sets of constraints are also imposed by the EU regulation on the construction of NZ portfolios. First, sin stocks should be excluded from the list of constituents of the climate index. This list includes firms in the following sectors: Tobacco, alcohol, gambling, sex-related industries, and weapons. On average, this restriction results in the exclusion of 12 firms (approximately 3.95% of the BAU benchmark market value in 2021 and approximately 5.07% on average from 2011-2021). We note that this constraint has a marginal impact on the portfolio WACI because these sectors are not carbon intensive.

Second, the PAB imposes the exclusion of firms with a significant share of their revenues derived from the coal, oil and gas sectors, as described in Section 2.1.1. The impact of this restriction is much more substantial. It implies the exclusion of 32 firms on average (40 in 2011, 28 in 2021) and results in a substantial reduction in portfolio carbon emissions, which we assess in the next section.

3. Results

We use historical data to simulate the annual reduction in a portfolio's carbon intensity over time. Specifically, we assess the effects of reducing carbon emissions each year from the end of 2011 (for 2012) through the end of 2020 (for 2021). By targeting a reduction trajectory that begins with an initial drop of 30% (CTB) or 50% (PAB), followed by a constant geometric decline of 7% per year over nine years, the WACI is reduced by 63.5% for CTB strategies and 74% for PAB strategies, as illustrated in Figure 5. In the following subsections, we discuss the advantages and challenges associated with the different investment strategies.

3.1. CTB versus PAB approaches

A key aspect of analyzing NZ strategies is the distinction between CTB and PAB approaches. As detailed, two differences characterize these benchmarks. First, the PAB approach is more ambitious, as it requires an initial 50% reduction in CO_2 emissions, while the CTB targets a 30% initial reduction. Second, consistent with this more stringent objective, the PAB approach excludes firms that derive a significant share of their revenues from fossil fuel activities. The impact of these different constraints is that the PAB achieves a larger overall reduction in carbon emissions after 10 years, approximately 63.5% for CTB and 74% for PAB.

the robust-minus-weak (RMW) factor, and the conservative-minus-aggressive (CMA) factor. They are obtained from Kenneth French's website: `https://mba.tuck.dartmouth.edu/pages/faculty/ken.french/data_library.html`. We use the factors computed for Europe and converted into EUR.

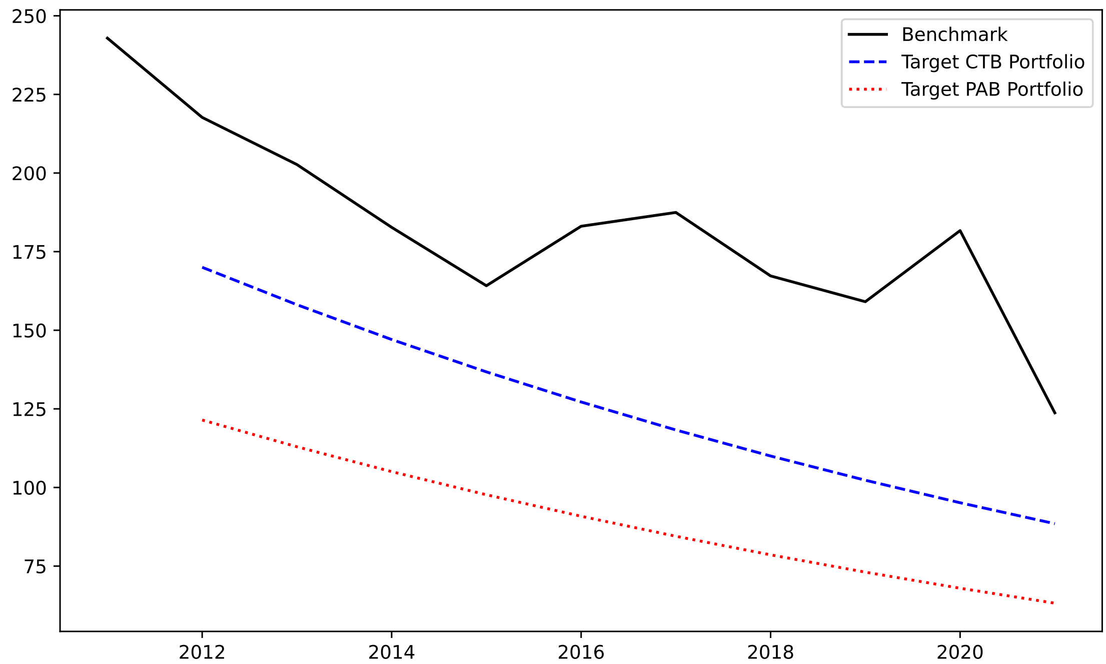


Figure 5. Evolution of the WACI of the benchmark and the CTB and PAB targets. (Note: This figure represents the evolution of the Scopes 1 and 2 WACI of the MSCI Europe benchmark and the implied evolution of the CTB and PAB climate indexes from 2011 to 2021. The WACI is measured in tCO_2e/mln EUR revenue.)

Our analysis is based on two major dimensions: The ex-post carbon performance and the ex-post financial performance of the climate index.

To better understand the underlying mechanisms driving decarbonization, we introduce a novel empirical decomposition of the reduction in portfolio's carbon intensity over time. This approach follows the major steps in the construction of CTB and PAB strategies and enables us to quantify the relative contributions of regulatory exclusions, active portfolio screening, reallocation effects, and firm-level emission reductions. We therefore provide new insights into how different NZ strategies deliver on climate targets. This decomposition is applied to the portfolio's ex-post WACI from the first year ($Y_1 = 2012$) to the final year ($Y_{10} = 2021$).[17]

We begin with the WACI of the BAU benchmark in the initial year ($WACI^{(b)}_{Y_0}$), which serves as the reference level of carbon intensity. We then consider the drivers of carbon emission reductions between $Y_1 = 2012$ and $Y_{10} = 2021$. Specifically, we identify three types of excluded firms: (1) Sin stocks; (2) companies with high revenue shares from fossil fuels, and (3) firms excluded based on their carbon intensity in 2021. We compute the contribution of each group to the portfolio WACI in the first year of implementation (2012), which we denote by $WACI^{(sin)}_{Y_1}$, $WACI^{(fossil)}_{Y_1}$ and $WACI^{(excl.)}_{Y_1}$, respectively. We then construct the portfolio p at the end of 2020 (for 2021) and measure the change in the WACI for the same portfolio from 2012 to 2021, which we denote by $\Delta WACI^{(p)}_{Y_1,Y_{10}} = WACI^{(p)}_{Y_{10}} - WACI^{(p)}_{Y_1}$.

[17]Alternative approaches would not allow us to measure the contribution of various components, notably the effect of firms' own decarbonization effort, to the overall reduction in portfolio WACI.

The full decomposition of the WACI change for the climate index portfolio over the sample period can be summarized as:

$$WACI^{(p)}_{Y_{10}} = WACI^{(b)}_{Y_0} - WACI^{(sin)}_{Y_1} - WACI^{(fossil)}_{Y_1} - WACI^{(excl.)}_{Y_1} + \Delta WACI^{(p)}_{Y_1,Y_{10}}. \tag{5}$$

The last term captures two effects: The change in portfolio weights relative to firms' carbon intensity in 2012 (called 'Reallocation') and the reduction in the carbon intensity of firms held in the portfolio by 2021 (called 'Firms' reduction'). This decomposition is expressed as:

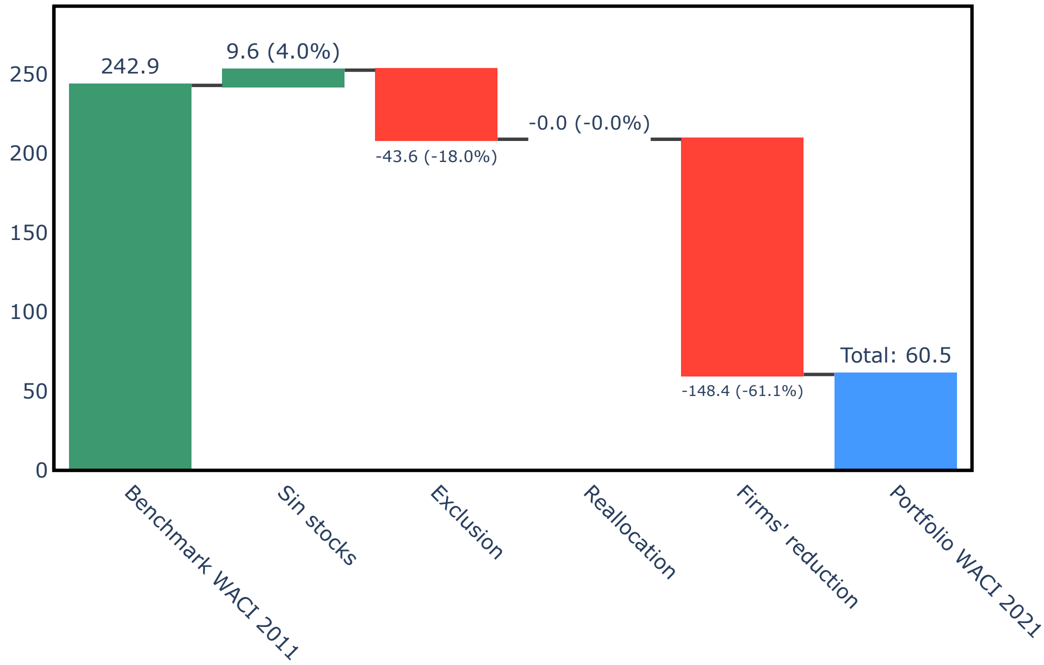
$$\Delta WACI^{(p)}_{Y_1,Y_{10}} = \underbrace{\sum_{i \in S^{(p)}_{Y_{10}}} (w_{i,Y_{10}} - w_{i,Y_1}) CI_{i,Y_1}}_{\text{Reallocation}} + \underbrace{\sum_{i \in S^{(p)}_{Y_{10}}} w_{i,Y_{10}} (CI_{i,Y_{10}} - CI_{i,Y_1})}_{\text{Firms' reduction}},$$

where $S^{(p)}_{Y_{10}}$ is the set of firms in the climate index portfolio in the final year.

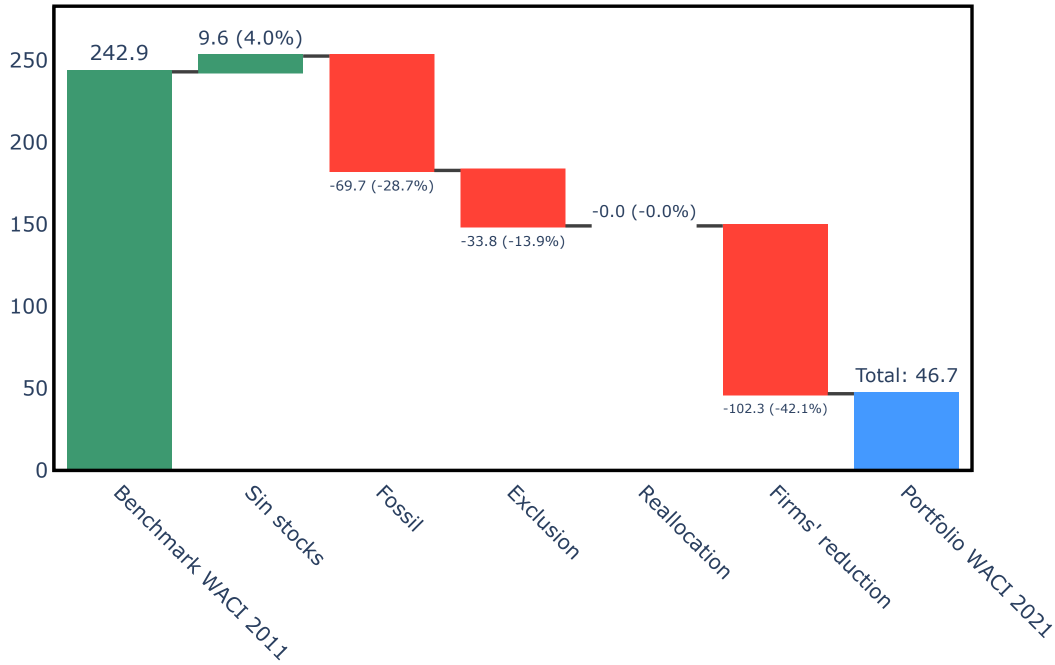
Figure 6 illustrates the contribution of these drivers for the CTB and PAB strategies between 2012 and 2021. The figure decomposes the reduction in portfolio carbon emissions into the contributions of sin stock exclusions, fossil fuel exclusions, firm-level exclusions based on carbon intensity, and changes attributable to portfolio reallocation and firm behavior. First, the apparent increase in WACI associated with the exclusion of sin stocks reflects that these firms tend to have relatively low carbon intensity. Therefore, excluding them and reallocating their weight to other, potentially more carbon-intensive firms, results in a 4% average increase in portfolio WACI. This counterintuitive result highlights the importance of evaluating exclusions not only from a compliance standpoint but also in terms of their practical emission impacts.

Second, it is worth emphasizing that the application of the exclusion rule for firms with a significant share of their revenues in fossil energy plays a large but decreasing role in the PAB. The number of excluded firms decreased from 40 in 2012 to 28 in 2021, so this rule contributed less to the overall decarbonization process over time (from 42% in 2012 to 29% in 2021). All major oil and gas firms (including BP, ENI, Shell, and TotalEnergies) would be excluded throughout the period. Importantly, this rule also led to the exclusion of several companies classified under materials and utilities (8 firms in both sectors), indicating that the systematic exclusion criterion is not limited to energy firms alone. We note that, because the energy sector is progressively excluded from the PAB due to this rule, the best-in-class method cannot be applied to this sector. As a result, the initial market value of the energy sector is reallocated proportionally to all other sectors.

The third component of decarbonization is the exclusion process itself, through which investors divest from some firms because of their high impact on portfolio's emissions. This exclusion has a greater impact in CTB than in PAB, as some high-emitting energy firms are not captured by the fossil fuel exclusion rule and are instead removed during this additional screening. Consequently, the contribution of the exclusion to overall WACI reduction is 17.9% for CTB and only 13.5% for PAB.



Panel A: CTB.



Panel B: PAB.

Figure 6. Decomposition of the carbon reduction of exclusion approaches. (Note: This figure represents the contribution to the reduction in carbon intensity based on Equation (5) for the CTB (Panel A) and PAB (Panel B) with exclusion. This figure presents a decomposition of the drivers behind carbon intensity reduction in CTB and PAB strategies over the 2012–2021 period. Using Equation (5), we isolate the contributions of the regulatory exclusions of sin stocks and fossil fuel firms (for PAB), the additional exclusion of high-intensity firms, the portfolio reallocation, and the firm-level reduction in carbon emissions. All values are expressed in tCO_2e/mln EUR revenue.)

The fourth component, i.e., the reallocation of firms within the portfolio, has no impact on portfolio's carbon intensity under the exclusion method, as proceeds are reinvested proportionately in all remaining firms. The last component corresponds to the reduction in firms' carbon intensity over the 10-year period. As many companies, especially high emitters, have significantly reduced their emissions, this reduction has been a major contributor to the decline in WACI for both CTB and PAB, by 61.1% and 42.1%, respectively. The gain is greater for the CTB portfolio because it includes some energy firms, which have shown greater emission reductions than firms in other sectors. This contribution represents a large fraction of the CTB target, which makes the CTB objective easier to achieve for the portfolio manager.

If we focus on the sectors most affected by screening strategies, we observe some significant differences between CTB and PAB, due to the latter's more stringent regulation of fossil fuel firms. In the PAB allocation for 2021, the rebalancing impact is particularly pronounced for energy, utilities, and materials, with 100%, 61%, and 70% of each sector's market value excluded from the climate index. A substantial share of firms in consumer staples (31.8%) is also excluded from the climate index, primarily because this sector includes firms specialized in alcohol and tobacco. In contrast, the remaining sectors experience moderate reallocation effects and may benefit slightly from the redistribution of the excluded energy sector's weight.

From a financial perspective, the CTB and PAB approaches have different implications: First, as expected, the PAB portfolio exhibits a high tracking error relative to the benchmark due to its stricter exclusion criteria. Overall, the ex-post annual tracking error is equal to 0.6% for CTB and 1.7% for PAB. Similarly, the portfolio turnover due to rebalancing is higher for PAB.[18]

Second, over the sample, the financial performance of CTB and PAB portfolios differ substantially. Annual returns are equal to 9.6% for CTB and 10.7% for PAB, with Sharpe ratios equal to 0.30 and 0.38, respectively. For comparison, the benchmark portfolio delivered an annual return of 9.46% and a Sharpe ratio of 0.29. These results suggest that, over the period, applying an exclusion screening would not have reduced financial performance. Moreover, imposing additional restrictions on energy firms would not have resulted in any negative financial impact.

3.2. Exclusion versus best-in-class methods

In the exclusion method, the proceeds from divesting from firms with the highest carbon intensity are reallocated proportionately to all remaining stocks in the portfolio. In the best-in-class method, the proceeds are reinvested in the firms with the lowest carbon intensity within the same sector. This method is particularly important because EU regulation explicitly states that NZ funds should not exclude sectors that are essential to the functioning and transition of the economy. From this perspective, the exclusion method would not directly qualify as an Article 9 fund. However, the best-in-class method also raises some practical challenges. As the PAB portfolio requires the exclusion of firms with a significant share of revenues in fossil energy activities, the portfolio's exposure to the energy sector is dramatically reduced, making it impossible to maintain sectoral weights consistent with the benchmark for this sector.

Our best-in-class method accounts for this limitation by treating the energy sector separately from the rest of the economy. We divest from energy firms when their revenues from coal, oil, and gas

[18]Turnover is defined as the sum over all the securities of the absolute rebalancing values, i.e., $TO_Y^{(p)} = \sum_{i=1}^{N_Y} |w_{i,Y} - w_{i,Y^-}|$, where w_{i,Y^-} is the weight of firm i just prior to rebalancing.

activities exceed a given threshold, but do not reinvest the proceeds in other energy firms. The reason for this decision is that very few firms remain in the sector after screening (typically only one or two), and overweighting these firms would result in excessive concentration. For all other sectors, we apply the best-in-class method, i.e., we reinvest proceeds in firms with the lowest carbon intensity within the same sector.

Consequently, the decomposition of the reduction in carbon emissions includes an additional component to account for reinvestment of the proceeds following exclusions. As reinvestment occurs at the sectoral level, reallocating proceeds to firms in carbon-intensive sectors can increase overall emissions, even if the selected firms are relatively less emitting within their sector. As this reinvestment increases the portfolio's carbon intensity, it is necessary to exclude more firms. Figures 6 and 7 illustrate this mechanism for CTB and PAB. For CTB, the reallocation slightly reduces the portfolio carbon intensity (by approximately 3%) because reallocating the proceeds of exclusion in the least-emitting firms within each sector leads to a more carbon-efficient allocation compared to a proportionate reinvestment.

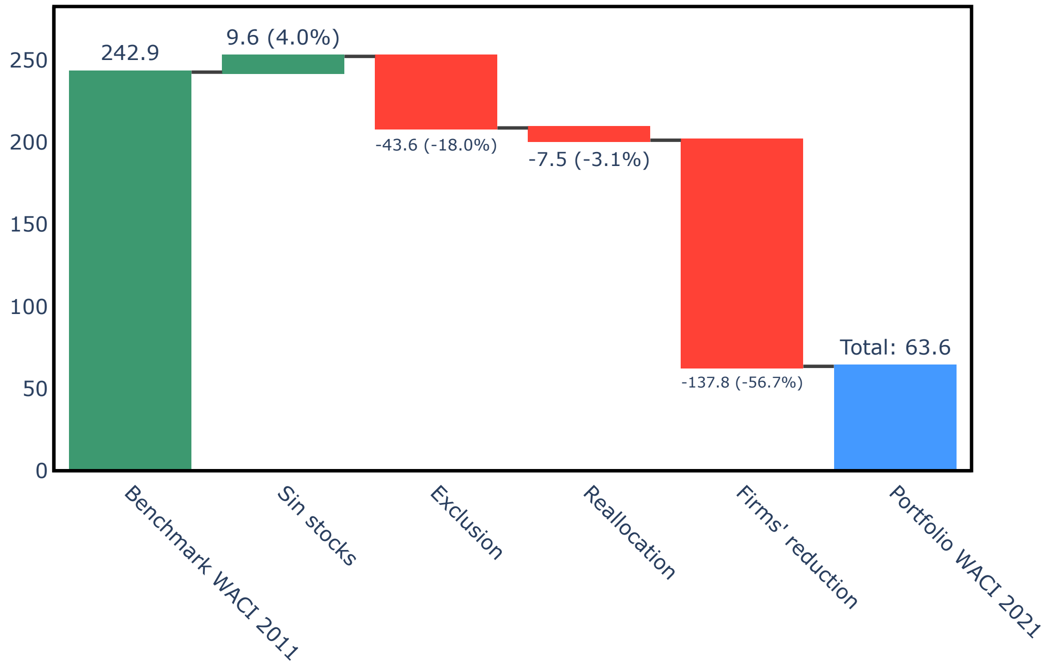
In the case of PAB, the exclusion method reduces emissions through the application of the fossil fuel rule (−28.7%) and additional direct exclusions (−13.9%). With the best-in-class method, the same reduction is obtained with the fossil fuel rule, but the proceeds are now reinvested in the same high-emitting sectors (except energy). As a result, more firms must be excluded to compensate for the reinvestment, increasing the contribution of the exclusion process to −16.6%. On the one hand, the reallocation process increases the portfolio carbon intensity by 21.1%, as proceeds are reinvested in firms from carbon-intensive sectors. On the other hand, as least-emitting firms in most-emitting sectors significantly improved their carbon performance over the period, the firms' reduction in carbon emissions has a substantial effect on the overall portfolio carbon intensity (−60.6%).

Regarding financial performance, the exclusion and best-in-class methods for the CTB result in similar portfolio characteristics: The tracking error and the financial performance are essentially the same. The reason is that the CTB reduction target is largely achieved through emission reductions at the firm level, requiring minimal portfolio reallocation. Consequently, the composition of the CTB portfolio is close to the BAU benchmark, and the contribution of the reallocation to the ex-post annual tracking error is minimal.

For PAB, which requires a more ambitious emission reduction, the reallocation burden is higher (34%). As the best-in-class method is less effective in reducing emissions, achieving the 76% reduction target requires greater rebalancing and therefore the tracking error increases from 1.66% to 2.16%. However, annual returns are only slightly reduced with the best-in-class method and the Sharpe ratio remains unaffected.

3.3. Tracking-error minimization and sectoral constraints

Previous research has shown that tracking-error minimization is very effective in decarbonizing portfolios (Andersson et al., 2016, and Bolton et al., 2022). The reason is that the optimization algorithm identifies the precise combination of stocks that meets the emission reduction target while minimizing deviations from the benchmark. One limitation of the approach in the context of an NZ portfolio is that it does not necessarily prevent the inclusion of high-emitting firms in the portfolio. We consider two alternative cases of tracking-error minimization. In the first case, we do not impose restrictions on sectoral exposures, which mirrors the logic of exclusion screening. In the second case, we follow the best-in-class rationale and preserve sector weights consistent with the BAU benchmark (except for energy).



Panel A: CTB.

Panel B: PAB.

Figure 7. Decomposition of the carbon reduction of Best-in-class approaches. (Note: This figure represents the contribution to the reduction in carbon intensity based on Equation (5) for the CTB (Panel A) and PAB (Panel B) with best-in-class. All values are expressed in tCO_2e/mln EUR revenue.)

These adjustments alter the decomposition of emission reductions. First, we measure the contribution of excluded firms in the minimization process. They usually correspond to firms with the highest carbon intensity. Second, we quantify the contribution of the optimization process itself, i.e., the reweighting of firms based on a trade-off between emissions and tracking error. This reallocation can in principle increase the portfolio WACI if it is optimal to invest in some high-emitting firms with a favorable tracking error profile.

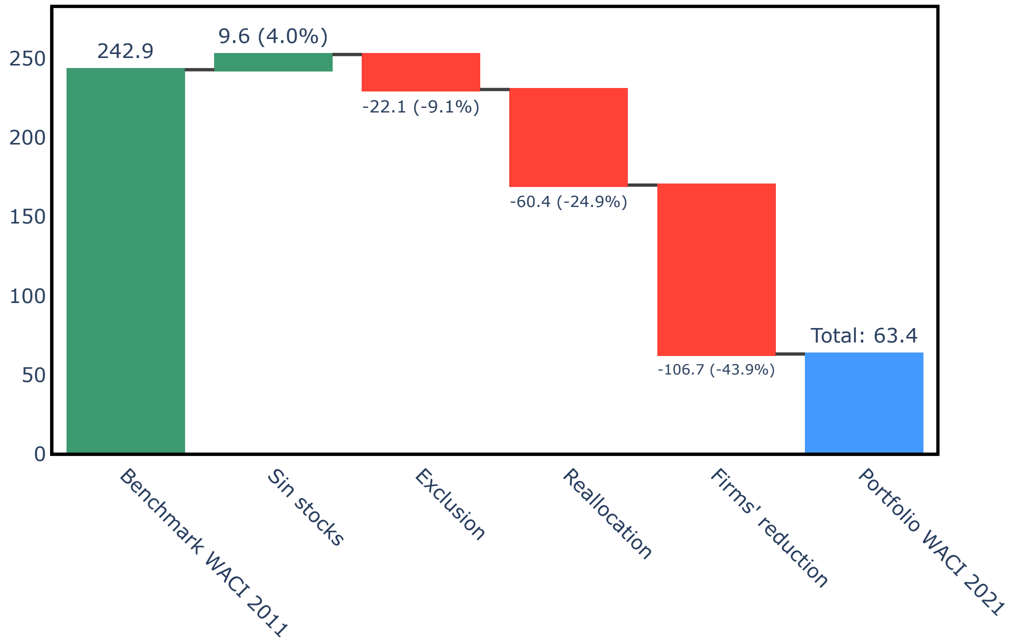
Figure 8 provides the decomposition of the carbon emission reduction for the case without sectoral constraints. Compared with the exclusion method (Figure 6), the optimization process excludes fewer firms and focuses more on the reallocation between stocks. Instead of fully divesting from a high-emitting firm, the algorithm may reduce its weight in combination with adjustments to other firms, achieving the same emission reduction with a lower impact on tracking error.

When sectoral constraints are imposed (Figure 9), the optimization excludes fewer firms than the best-in-class method (Figure 7). For PAB, the contribution from firm exclusions is 11.1% under tracking-error minimization, compared to 16.6% under best-in-class. The difference stems from the flexibility of the optimization approach, which enables partial weighting of high-emitting firms than full exclusion. In fact, some firms retained under the tracking-error minimization approach substantially reduced their emissions, which increases the contribution of firm-level decarbonization. As a result, the reduction in WACI attributable to emission reductions is higher under the optimization strategy than under the best-in-class method (30.3% vs. 24.9%).

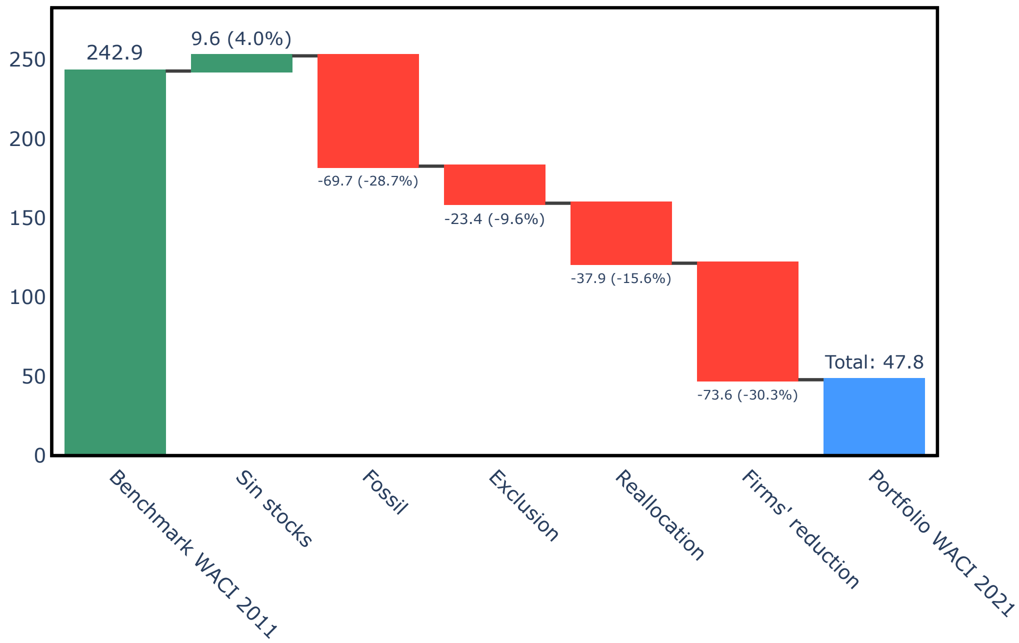
As for the screening strategies, the main distinction between tracking-error minimization strategies is the size of the tracking error relative to the BAU benchmark for CTB and PAB. When sectoral constraints are imposed, the ex-post annual tracking error is equal to 0.86% for CTB and 1.74% for PAB. However, Table 2 also reveals that portfolio turnover is significantly higher under the tracking-error minimization approach than under screening strategies. The annual turnover is as high as 23.2% for PAB, compared to 13.6% under the best-in-class method. Such a difference reflects the main feature of the tracking-error minimization: It enables for substantial reallocation between firms to meet emission reduction targets while minimizing deviations from the benchmark. Such flexibility comes at the cost of increased turnover, which may have implications for transaction costs and portfolio stability.

Otherwise, the financial performance is comparable across the different methods. In particular, both the annual return and the Sharpe ratio remain higher than those of the benchmark. These results suggest that investing in an NZ strategy entails only marginal costs in terms of tracking error. The only significant cost arises from the imposition of sectoral constraints, which contribute to a higher tracking error.

One notable difference between the best-in-class method and the tracking-error minimization is the magnitude of overweighting. In the best-in-class method, firms that are overweighted (typically those with the lowest carbon emissions within each sector) receive a uniform relative increase in portfolio weight. By contrast, under tracking error minimization, all firms that are not excluded based on fossil fuel revenue share will be reweighted to simultaneously satisfy the carbon emission reduction target and minimize the tracking error. As a result, some firms with relatively high carbon intensity may become substantially overweighted.

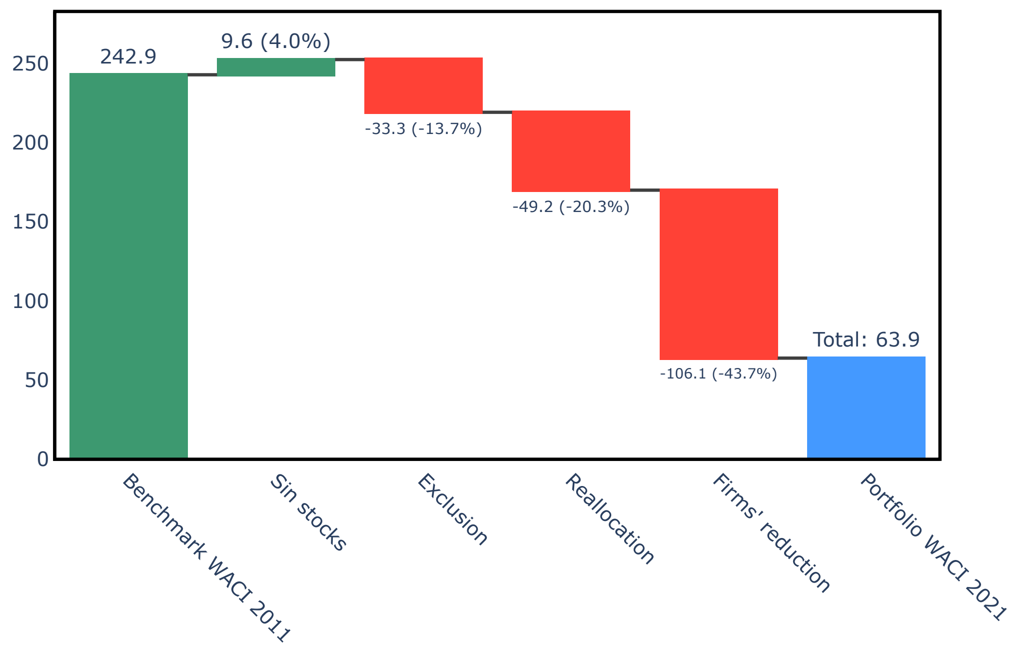


Panel A: CTB.

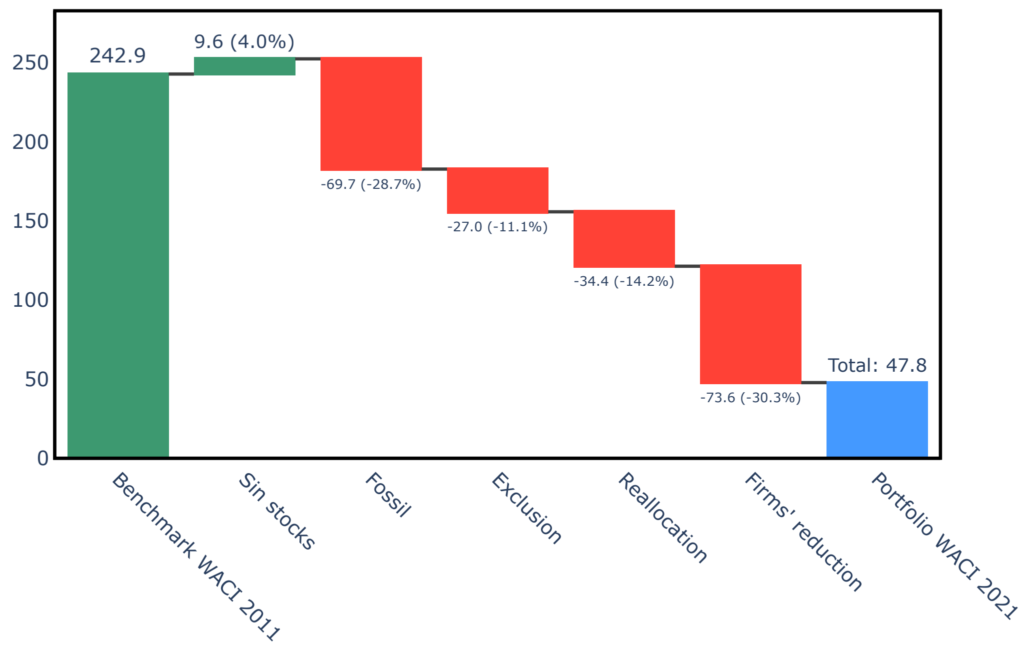


Panel B: PAB.

Figure 8. Decomposition of the carbon reduction of tracking error approaches without sectoral constraints. (Note: This figure represents the contribution to the reduction in carbon intensity based on Equation (5) for the CTB (Panel A) and PAB (Panel B) with tracking-error minimization. All values are expressed in tCO_2e/mln EUR revenue.)



Panel A: CTB.



Panel B: PAB.

Figure 9. Decomposition of the carbon reduction of tracking error approaches with sectoral constraints. (Note: This figure represents the contribution to the reduction in carbon intensity based on Equation (5) for the CTB (Panel A) and PAB (Panel B) with tracking-error minimization and sectoral constraints. All values are expressed in tCO_2e/mln EUR revenue.)

Table 2. NZ Portfolios based on Scopes 1 and 2 carbon intensity.

	Benchmark	Exclusion		Best-in-class (sect. constr.)		Min TE		Min TE (sect. constr.)	
		CTB	PAB	CTB	PAB	CTB	PAB	CTB	PAB
Carbon Metrics									
Reduction Target (%)	–	66.12	75.80	66.12	75.80	66.12	75.80	66.12	75.80
Carbon intensity reduction (%)	0.49	75.05	80.76	73.81	80.84	73.91	80.32	73.68	80.31
Financial Performance									
Annual return (%)	9.46	9.57	10.74	9.55	10.69	9.66	10.90	9.46	11.01
Annual volatility (%)	16.02	16.15	16.00	15.78	15.47	16.03	15.93	15.86	15.79
Sharpe ratio	0.29	0.30	0.38	0.31	0.39	0.31	0.39	0.30	0.40
Annual ex-post tracking error (%)	–	0.60	1.66	0.56	1.79	0.50	1.59	0.86	1.74
Turnover (%)	11.00	9.64	11.11	10.55	13.35	9.32	13.94	16.89	23.24
Risk Factor Exposures									
Alpha (%)		1.69 [a]	1.78 [a]	1.68 [a]	1.76 [a]	1.69 [a]	1.77 [a]	1.69 [a]	1.76 [a]
Market portfolio		0.97 [a]	0.98 [a]	0.96 [a]	0.96 [a]	0.96 [a]	0.97 [a]	0.95 [a]	0.97 [a]
SMB portfolio		-0.33 [b]	-0.33 [b]	–0.33 [b]	–0.32 [b]	–0.33 [b]	–0.30 [b]	–0.32 [b]	–0.26 [c]
HML portfolio		0.31	0.21	0.27	0.16	0.30	0.24	0.30	0.22
RMW portfolio		–0.01	–0.08	0.03	–0.02	0.01	0.02	–0.01	0.02
CMA portfolio		–0.62 [b]	–0.61 [b]	–0.58 [b]	–0.59 [b]	–0.61 [b]	–0.58 [b]	–0.62 [b]	–0.60 [b]
Adjusted R^2 (in %)		0.76	0.77	0.75	0.75	0.76	0.76	0.75	0.76

Note: This table reports, for each portfolio built using a target of scope 1 and 2 carbon intensity, the following carbon and financial metrics: The carbon reduction target (in %), and the ex-post carbon intensity reduction (in %). The annualized return (in %), the annualized volatility (in %), the Sharpe ratio, the annual ex-post tracking error (in %), and the annual portfolio turnover (in %). Risk factor exposures are estimated parameters when excess returns associated with the different strategies are regressed on the five Fama-French risk factors. [a], [b], and [c] mean that the associated parameter is significant at the 1%, 5%, and 10% significance level.

This phenomenon is particularly visible in the materials and utilities sectors. Among materials firms, in 2020, Evonik Industries and Covestro had the 32nd and 35th highest carbon intensities in the BAU benchmark (656 and 578 tCO_2e/mln EUR revenue, respectively), yet their weights under tracking-error minimization are multiplied by 1.9 and 2.1 in the climate index relative to the BAU benchmark, respectively. In contrast, these firms are excluded from the climate index with the best-in-class method. Similarly, Red Electrica, the Spanish national electricity grid operator, has 58th highest carbon intensity in the BAU benchmark (331 tCO_2e/mln EUR revenue), yet its weight under tracking-error minimization is multiplied by 4.7 in the climate index relative to the BAU benchmark. Under the best-in-class method, the weight increases by a more moderate factor of 2.7.

From a financial perspective, PAB outperforms CTB across all strategies considered, as reflected in both annual return and Sharpe ratio. This is notable given that PAB excludes the energy sector entirely. The last panel of the table reports risk factor exposures, i.e., parameters associated with the regression of a portfolio's excess returns on the five Fama-French risk factors. For all strategies, the parameters associated with the market portfolio are close to 1 and statistically significant, confirming that the NZ strategies implemented in the paper closely track the benchmark. The NZ strategies also exhibit significant and negative exposures to the SMB and CMA factors, suggesting that the portfolios tend to overweight small and aggressive firms, including small firms in the renewable and tech industries. Risk-adjusted performance values (alphas) are all positive and statistically significant, with PAB portfolios exhibiting higher performance than CTB portfolios. This result is confirmed in Figure 10, which shows the cumulative performance for both the best-in-class (Panel A) and tracking-error minimization (Panel B) approaches. These results might be partly driven by our sample period.[19] Moreover, including 2022 in the sample might reduce the benefit of excluding energy firms for PAB. From this perspective, the impact of the energy transition on the relative performance of CTB and PAB remains uncertain. A successful transition would likely favor PAB, while a delayed transition could benefit CTB more.

3.4. Scopes 1 and 2 versus scopes 1, 2, and 3 upstream

The results discussed so far are based on Scopes 1 and 2 carbon emissions. The major reasons for this focus are that Scopes 1 and 2 emissions are under the direct control of firms and that their disclosure is mandatory, and therefore directly measured by firms. In contrast, Scope 3 upstream emissions are typically estimated based on sectoral proxies and are subject to greater uncertainty in both measurement and reporting. However, EU regulation states that NZ strategies should gradually transition from Scopes 1 and 2 to broader coverage, including Scope 3 emissions.[20] As a result, although not yet universally required, investors will eventually integrate Scope 3 data into their portfolio construction.

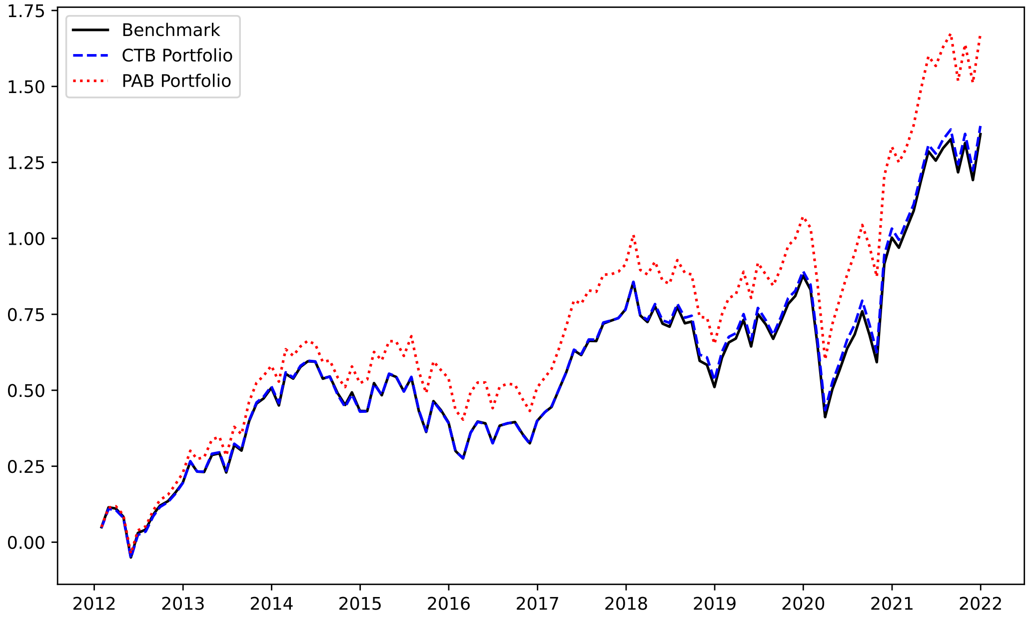
To anticipate this regulatory shift, we extended our analysis to include Scope 3 upstream emissions in the carbon intensity metric. The contribution of Scope 3 upstream emissions to total (Scopes 1, 2, and 3 upstream) emissions can be particularly large in some sectors, confirming empirical evidence reported by Le Guenedal and Roncalli (2022). For instance, Scope 3 upstream accounts for 88.6%, 85.6%, 84.6%, and 50.2% of total emissions in the consumer discretionary, consumer staples, financials, and energy sectors, respectively.[21]

The results based on emissions that include Scopes 1, 2, and 3 upstream are summarized in Table 3. A key insight is that the reduction in firms' carbon intensity over the sample period is much more limited when including Scope 3 upstream emissions, compared to using only Scopes 1 and 2. For example, the BAU benchmark carbon intensity declines by just 30% rather than 49%. This smaller decline implies that NZ strategies must reallocate a greater share of the portfolio to meet their emission reduction targets. Consequently, achieving the same decarbonization trajectory becomes more complex and more costly. These additional costs are reflected in significant increases in both tracking error and turnover across all strategies. The effect is particularly pronounced for CTB portfolios, where tracking errors rise by more than 50% for all strategies and nearly triple for the best-in-class strategy. The corresponding increase in turnover suggests that the reduction in carbon intensity is now primarily achieved through more aggressive portfolio reallocation. This mechanism is further illustrated in Figure 11, which presents the decomposition of carbon emission reductions for both the best-in-class and tracking-error minimization methods.

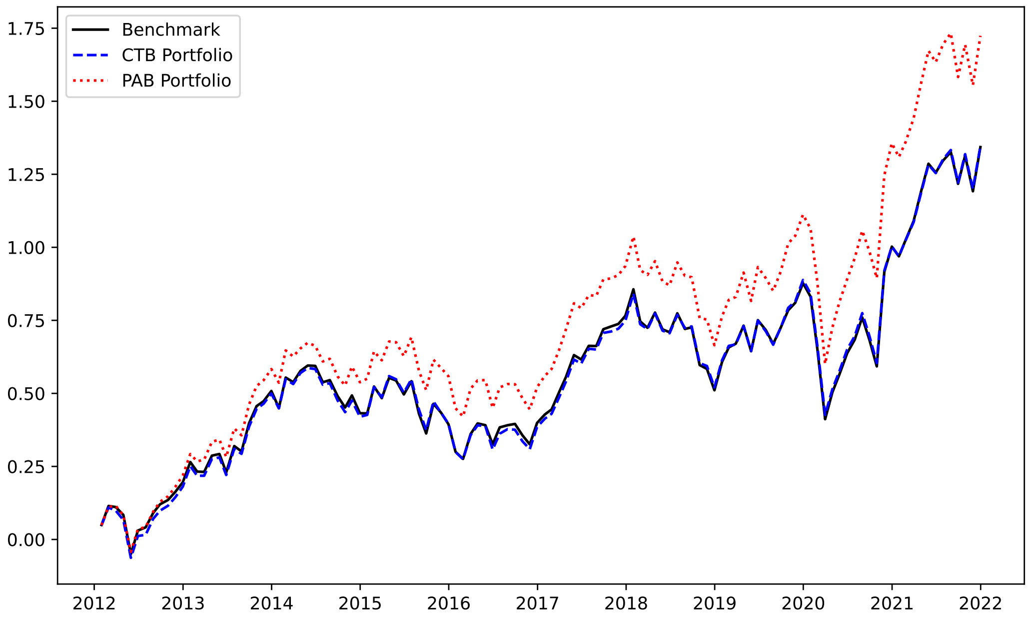
[19] We did not include 2022 in our analysis, as carbon emission data were unavailable in our database.

[20] According to Regulation (EU) 2016/1011, 2016, Scope 3 GHG emission data shall be phased in as follows: For the energy and mining sectors, at the time of implementation (December 23, 2020); for the transportation, building, materials, and industrial sectors, two years post-implementation; and for all remaining sectors, four years post-implementation.

[21] Scope 3 downstream emissions, which are associated with the use phase of a firm's goods and services, can also represent a significant share of total emissions. However, these data are estimated with considerable uncertainty and lack historical depth. For this reason, Scope 3 downstream emissions are not included in our analysis.

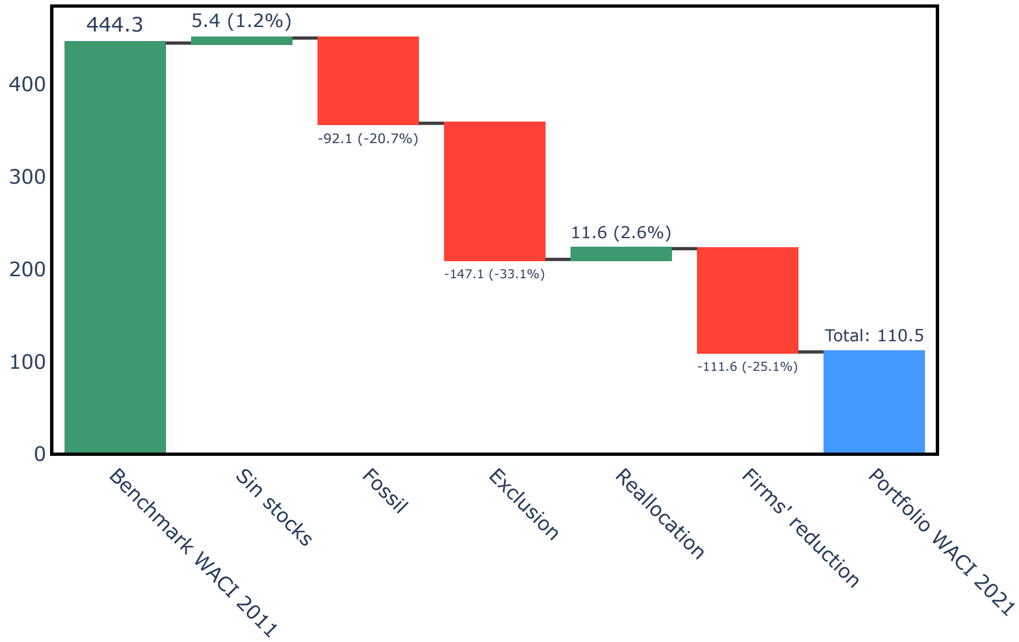


Panel A: Best-in-Class approaches.

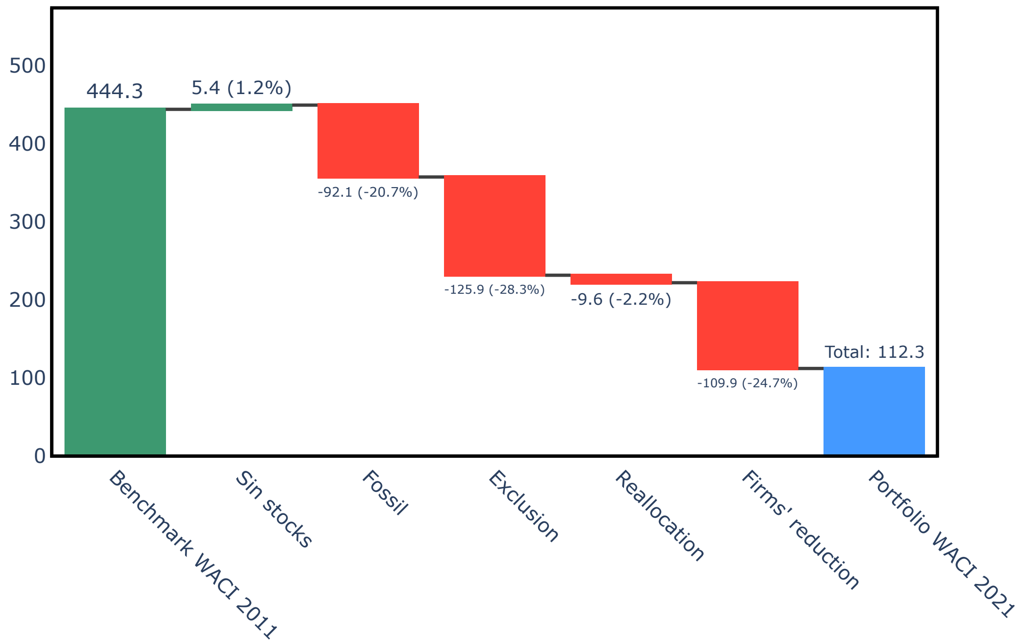


Panel B: tracking-error minimization approaches.

Figure 10. Cumulative returns. (Note: This figure represents the cumulative return of the CTB and PAB approaches of the best-in-class strategy (Panel A) and the tracking-error minimization strategy (Panel B). All series start at 0 in December 2011).



Panel A: Best-in-class PAB.



Panel B: Tracking-error minimization PAB.

Figure 11. Decomposition of the Carbon Reduction with Scope 3 Upstream with sectoral constraints. (Note: This figure represents the contribution to the reduction in carbon intensity based on Equation (5) for the best-in-class PAB (Panel A) and tracking-error minimization PAB (Panel B) with sectoral constraints, based on scopes 1, 2, and 3 upstream carbon intensity. All values are expressed in tCO_2e/mln EUR revenue.)

Table 3. NZ portfolios based on scopes 1, 2, and 3 upstream carbon intensity.

	Benchmark	Exclusion		Best-in-class (sect. constr.)		Min TE		Min TE (sect. constr.)	
		CTB	PAB	CTB	PAB	CTB	PAB	CTB	PAB
Carbon Metrics									
Reduction Target (%)	–	66.12	75.80	66.12	75.80	66.12	75.80	66.12	75.80
Carbon intensity reduction (%)	0.30	65.71	75.13	66.30	75.14	66.17	75.11	66.40	74.73
Financial Performance									
Annual return (%)	9.46	9.66	10.88	10.24	11.00	9.65	10.45	9.59	10.92
Annual volatility (%)	16.02	16.28	16.41	15.70	15.22	16.13	16.04	15.6	15.20
Sharpe ratio	0.23	0.30	0.38	0.35	0.41	0.31	0.36	0.31	0.41
Annual ex-post tracking error (%)	–	0.90	1.83	1.45	2.02	0.73	1.66	1.39	2.16
Turnover (%)	11.00	10.75	12.63	15.50	17.53	10.35	16.10	25.51	23.33
Risk Factor Exposures									
Alpha (%)		1.67^a	1.77^a	1.70^a	1.82^a	1.69^a	1.74^a	1.69^a	1.81^a
Market portfolio		0.44^b	0.42^b	0.42^b	0.40^b	0.43^b	0.41^b	0.41^b	0.38^c
SMB portfolio		1.14^b	1.18^b	1.20^b	1.12^b	1.15^b	1.18^b	1.14^b	1.11^b
HML portfolio		1.32^b	1.32^b	1.32^b	1.29^b	1.32^b	1.33^b	1.31^b	1.30^b
RMW portfolio		2.08^a	2.06^a	2.11^a	2.12^a	2.07^a	2.10^a	2.07^a	2.12^a
CMA portfolio		0.14	0.12	0.12	0.14	0.16	0.13	0.10	0.09
Adjusted R^2 (%)		0.16	0.15	0.16	0.14	0.16	0.15	0.15	0.14

Note: This table reports, for each portfolio built using a target of scope 1 and 2 carbon intensity, the following carbon and financial metrics: The carbon reduction target (in %), and the ex-post carbon intensity reduction (in %). The annualized return (in %), the annualized volatility (in %), the Sharpe ratio, the annual ex-post tracking error (in %), and the annual portfolio turnover (in %). Risk factor exposures are estimated parameters when excess returns associated with the different strategies are regressed on the five Fama-French risk factors. ^{a}, ^{b}, and ^{c} mean that the associated parameter is significant at the 1%, 5%, and 10% significance level.

Despite these higher implementation costs, the risk-adjusted financial performance of NZ portfolios is barely affected by the inclusion of Scope 3 upstream emissions. Sharpe ratios remain nearly identical to those observed using only Scopes 1 and 2, and they consistently outperform the Sharpe ratio of the BAU benchmark. These findings suggest that financial performance is not primarily driven by divestment from a subset of high-emitting firms, but reflects the broader composition and optimization of the portfolio.

4. Conclusions

Our empirical analysis yields three findings. First, an NZ investment strategy aligned with the requirements of EU SFDR Article 9(3) can be implemented at marginal financial cost, at least over a 10-year horizon. CTB portfolios achieve their decarbonization objectives with a minimal tracking error (between 0.6% and 0.8% per year) and similar risk-adjusted performance. In contrast, the more ambitious PAB portfolios require moderate tracking errors (around 1.7%–1.8%) but result in substantially higher risk-adjusted performance. Notably, over the 10-year period, PAB outperforms CTB across all strategies in terms of both carbon and financial performance. Second, alternative portfolio construction techniques (exclusion/best-in-class and tracking-error minimization) achieve comparable results in terms of carbon reduction and financial performance, with minimal impact on sectoral and factoral exposures. tracking-error minimization achieves lower tracking error but tends to concentrate portfolio weights, potentially raising concerns about liquidity and diversification. Third, our decomposition reveals that a large share of the WACI reduction stems from the exclusion of high-emitting firms and corporate emission reductions. This result suggests that investors implementing an NZ strategy might continue benefiting from the ongoing decarbonization process at the industry level. Importantly, the current reduction in carbon emissions is not aligned with the ambitious target of the Paris Agreement but it helps investors reduce the portfolio WACI.

Our findings have practical implications for regulators, particularly in the context of the ongoing review of the SFDR framework. The current regulation imposes a requirement that, except for the energy sector, sectoral exposures should be maintained for Article 9(3) funds. This condition may prove difficult to uphold in practice, especially in high-emitting industries where few firms meet sustainability thresholds. In this regard, the discussions led by the ESAs provide an opportunity to address the distinction between sustainability and transition strategies, as opposed to broad Article 8 and 9 categories. Interestingly, according to the Platform on Sustainable Finance (2024), PAB approaches (with more stringent exclusion rules) typically correspond to sustainability products because target companies are already aligned with the environmental and social objectives. In contrast, CTB approaches are more closely associated with transition products, as they invest in companies that are not yet aligned but are on a credible decarbonization path.

The move toward sustainability and transition categories would be aligned with our empirical findings that PAB is clearly more ambitious than CTB with different objectives: PAB fits sustainability due to its strict exclusions and alignment. CTB and tracking-error minimization are a more natural fit for transition products, focusing on decarbonization at lower cost.

Our results are likely to remain valid regardless of future reforms because the core mechanics of NZ portfolio construction are unlikely to change. However, the adoption of more standardized guidance could reduce implementation costs and help align regulatory intent with investment practice.

Building NZ portfolios that achieve substantial emission reductions over a relatively short time horizon is both feasible and financially viable, at least within our historical sample. In the short run, portfolio carbon footprints can be lowered through rebalancing at a moderate cost, by excluding high-emitting firms and reallocating toward lower-emitting ones. However, as the pool of eligible firms shrinks, this approach will likely generate rising tracking errors, eroding the appeal of NZ strategies for institutional investors, especially those with passive mandates. Therefore, in the long term, the success of NZ strategies will increasingly depend on the real-world decarbonization of the economy, particularly the ability of high-emitting firms to significantly reduce their carbon intensity.

Importantly, NZ strategies are not only shaped by the real economy; they can also help shape it. While the impact of a single investor's exclusion strategy may be marginal, collective NZ action at scale (through alliances or coordinated capital shifts) can increase the cost of capital for high-emitting firms, making brown investments less attractive, and accelerating the competitiveness of green technologies. This feedback loop suggests that NZ investing is not just a reflection of climate progress, but a potential driver of it.

For NZ strategies to remain effective and scalable, they must be embedded within a broader economic transition. This means that investor action alone is not enough; it must be matched by credible corporate transition plans and sustained reductions in firm-level emissions. If countries fulfill their Paris Agreement commitments, much of the emission reduction in NZ portfolios will result from firms cleaning up their operations, thereby easing the burden on portfolio construction. However, if the global economy fails to decarbonize at the required pace, NZ investing will become more costly and less efficient, potentially undermining financial performance and climate credibility.

Author contributions

All authors contributed equally to the conception, design, analysis, and writing of the paper. All authors have read and approved the final manuscript.

Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

Conflict of interest

All authors declare no conflicts of interest in this paper.

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