INTEGRATING THE CARBON FOOTPRINT INTO THE CONSTRUCTION OF CORPORATE BOND PORTFOLIOS

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Abstract

Institutional investors, aware of the need to incorporate climate change as an additional risk factor into portfolio management, show a growing appetite for integrating Sustainable and Responsible Investment (SRI) criteria into their investment processes. Within a passive management context, this paper analyses, from a practical point of view, the inclusion of such criteria in the construction of corporate bond portfolios, thus incorporating a new dimension into the asset allocation process. We study the decarbonisation of a euro area corporate bond portfolio by constructing the efficient frontier, which shows the trade-off between the portfolio's decarbonisation possibilities and the cost assumed in terms of deviation from the benchmark portfolio. We also analyse the impact of decarbonisation on the different risk-return parameters during the asset reallocation process. Finally, we present the main green investment strategies that investors can use to incorporate sustainability criteria into corporate bond portfolios' design, introducing the Green-Parity approach as a complementary strategy to the available toolkit. The result of our empirical analysis, for the selected investment universe and sample period, shows that sustainability-conscious corporate bond investors have at their disposal different strategies that will allow them to achieve their decarbonisation objective without having to deviate significantly from their benchmark portfolio and to adequately meet the purely financial goals dictated by their investment mandate.

Keywords: sustainable investments, carbon footprint, decarbonisation, climate risk, fixed income portfolio management, asset allocation, Green-Parity.

JEL classification: G10, G11, G12, M14, Q50.

Resumen

Los inversores institucionales, conscientes de la necesidad de incorporar el cambio climático como un factor de riesgo adicional en la gestión de carteras, muestran un apetito creciente por la integración de criterios de Inversión Sostenible y Responsable (ISR) en sus procesos de inversión. En un contexto de gestión pasiva, este trabajo analiza, desde un punto de vista práctico, la inclusión de dichos criterios en la construcción de carteras de bonos corporativos, incorporando así una nueva dimensión al proceso de asignación de activos. Estudiamos la descarbonización de una cartera de bonos corporativos europeos mediante la construcción de la frontera eficiente, que muestra la relación entre las posibilidades de descarbonización de la cartera y el coste asumido en términos de desviación de la cartera de referencia. También analizamos el impacto de la descarbonización en los diferentes parámetros de riesgo-retorno durante el proceso de reasignación de activos. Finalmente, presentamos las principales estrategias de inversión verde que los inversores pueden utilizar para incorporar criterios de sostenibilidad en el diseño de carteras de bonos corporativos, introduciendo el enfoque de Green-Parity como estrategia complementaria al conjunto de herramientas disponible. El resultado del análisis empírico, para el universo de inversión y período elegidos, muestra que el inversor en bonos corporativos preocupado por la sostenibilidad tiene a su disposición diferentes estrategias que le permitirán lograr su objetivo de descarbonización sin tener que desviarse, significativamente, de su cartera de referencia y cumplir adecuadamente con los objetivos puramente financieros dictados por su mandato de inversión.

Palabras clave: inversiones sostenibles, huella de carbono, descarbonización, riesgo climático, gestión de carteras de renta fija, asignación de activos, Green-Parity.

Códigos JEL: G10, G11, G12, M14, Q50.

1 Introduction

Climate change and the transition to a low-carbon economy have become part of our society's urgent and unavoidable agenda. Institutional investors need to respond to the risks and opportunities brought about by the climate challenge in the construction and management of their investment portfolios. In that respect, a growing appetite and need call for the inclusion of sustainable and responsible criteria in the investment process.

Most of the existing research on which approaches to adopt to include such sustainable investment criteria in portfolio construction exercises has traditionally focused on equity assets, while there has been less application to fixed income instruments. In recent years, despite the challenges of integrating SRI factors into the asset allocation process, both academia and investors are paying particular attention to this segment of the capital market, given the importance of bond issuance in funding the energy transition and achieving sustainable development goals. In the case of fixed income, investment processes are less developed and adapted to integrate climate risk considerations compared with the progress made for equity portfolios.

This paper aims to contribute to the incipient analysis of the inclusion of climate change criteria in fixed income investment processes, incorporating, from an eminently empirical approach, two aspects considered to be of utmost importance: the cost of decarbonisation and the selection of the SRI portfolio construction strategy.

Among the main results obtained for the benchmark portfolio and sample period used, we find that the decarbonisation process involves an increasing cost in terms of deviation in the risk assumed from the benchmark portfolio, meaning that passive investors assume greater active risk in order to achieve their sustainability targets. We present the Green-Parity strategy, which yields the most favourable results in terms of relative green performance ratios compared with the other strategies used in the study. Finally, we find that there is not necessarily a penalty, in terms of risk-return, derived from the achievement of the decarbonisation objectives, although this conclusion could be affected if variations in the risk factors were allowed.

The remainder of the paper is structured as follows. After a brief literature review in Section 2, Section 3 presents the detailed methodology and description of the dataset used for the analysis. Within a passive management framework, we construct an initial reference portfolio (benchmark) built on market criteria and composed of bonds issued by a set of euro area non-financial corporations, upon which a decarbonisation target is established. Section 4 derives the efficient frontier that relates, for each level of carbon footprint, the associated minimum tracking error (TE) of the portfolio, i.e., we estimate the cost, or trade-off, in terms of deviation from the benchmark involved in reducing the carbon intensity of the portfolio. The impact on traditional risk and return metrics is analysed for these optimal (i.e., minimum TE) decarbonised portfolios. In Section 5, different green strategies for the construction of bond portfolios are analysed and compared, such as exclusion techniques, best-in-class, tilting, or the Green-Parity approach, all of them with the common objective of achieving, starting from an initial reference portfolio, the desired reduction in the carbon footprint. Subsequently, after analysing the impact of the different solutions on the reallocation of assets and the carbon footprint, the resulting financial metrics are obtained. Section 6 presents the conclusions and future lines of work.

2 Literature review

The traditional approach to managing the climate risk of an investment portfolio focuses on reducing the carbon footprint measured, for example, by the greenhouse gas emissions (GHG) of the issuers in the portfolio. The fundamental assumption underlying this approach is that, should such climate risk materialise in the future, the investor will experience more losses if they hold, in their overall portfolio, greater exposure to companies with a large carbon footprint.

The analysis presented in this paper follows the approach of Pedersen et al. (2021), Andersson et al. (2016) and Roncalli et al. (2020 and 2021). Pedersen et al. incorporate SRI considerations into the traditional CAPM theoretical framework, proposing an empirical ESG-efficient frontier that shows the costs and benefits of responsible investment for equity portfolios. Although also applied to equity portfolios, Andersson et al. construct a dynamic investment strategy benchmarked to a low-carbon (decarbonised) index, using exclusion and screening techniques, which halve carbon intensity, while maintaining neutrality in sectoral composition and a low TE against the benchmark.

Roncalli et al. use a mean-variance optimisation framework, in which they introduce constraints on carbon risk by combining direct or fundamental metrics such as the Weighted Average Carbon Intensity (WACI) with market metrics (the estimated carbon beta for each company) to construct different optimal portfolios with lower relative exposure to carbon risk than the benchmark, the MSCI World stock index.

In similar exercises, within the same theoretical framework and applied to the DJIA stock index, Qi and Li (2020) construct the efficient frontier with SRI restrictions and compare the results, in terms of risk-return and asset composition, with those of a conventional portfolio, while Schmidt (2020) incorporates the investor's SRI preferences into the objective function, introducing the concept of a sustainability-biased Sharpe ratio.

Finally, as a significant reference for research in fixed income portfolios, it is worth highlighting Ben Slimane et al. (2019). These authors attempt to estimate the impact of sustainable investment on corporate debt market pricing, as well as the effect of exclusion strategies in active and passive fixed income management. Regarding passive management, Ben Slimane et al. (2020) find a positive relationship between the improvement of SRI metrics and active risk versus the benchmark portfolio for the European investment-grade corporate bond market. Another paper also worthy of note is Pereira, Cortez and Silva (2019), who show that investors can construct bond portfolios based on sustainability criteria (social factor) without compromising financial performance.

3 Methodology and data

3.1 Definition of the eligible universe and the reference portfolio

The analysis is based on an initial benchmark portfolio ('b') composed of bonds from 19 euro area corporate issuers with an investment-grade credit rating, i.e., with a rating above BBB-. To construct it, weights are allocated to the different issuers following a market criterion, weighting each of the companies by their long-term debt level. Likewise, each company 'i' has an associated carbon footprint (carbon intensity or $\mathcal{CI}_i$).

The carbon footprint of a fixed income portfolio attempts to measure the volume of GHG emissions produced by the investments that make up the portfolio. Generally, the Taskforce on Climate-related Financial Disclosures (TCFD)[1] recommends WACI be used as the preferred metric for measuring the footprint, due to its simplicity and comparability across financial asset classes. An alternative metric frequently used in the analysis of climate risk in financial asset portfolios is each company's ESG score. ESG scores are ratings, issued by independent agencies, on the environmental, social, and corporate governance risk profile of companies and their ability to manage these risks in the future. In this paper, we have opted to use carbon intensity as the climate risk metric, not only due to its simplicity but also because the lack of consistency across the ESG scores of the different information providers and the low correlation between this latter metric and the carbon footprint complicate analysis.

The carbon intensity of a company is defined as the average volume of metric tonnes of CO_2 equivalent[2] emitted by that company in a year divided by its annual sales figure in millions of euro. This relative metric, which normalises emissions by sales or revenues of each company, allows for better comparison between different issuers, avoiding the introduction of biases due to the companies' different sizes.[3] Another advantage of using it, compared with absolute metrics, is that it reduces the distribution kurtosis.

Let us define:

$b = (b_1, \dots, b_n) =$ vector of weights of the benchmark 'b' portfolio

$\mathcal{CI}_\mathrm{i}$ = carbon footprint or carbon intensity of company 'i'.

The carbon footprint of the benchmark portfolio, or WACI, is calculated as the weighted average carbon intensity of the different 'i' issuers:

$$\mathcal{CI}\,(b) = \sum_{i=1}^{n} b_i\, \mathcal{CI}_i = b^T\, \mathcal{CI}$$

Table 1 shows the set of companies, country of origin, GICS sector and industry classification, long-term debt and reported carbon footprint for 2020. The WACI of the portfolio amounts to 303.4 tCO_2e/sales. Chart 1 shows the issuer distribution in the benchmark portfolio and its sectoral composition.

1 Final Report. Recommendations of the Task Force on Climate-related Financial Disclosures', pp. 36-37, GHG Emissions Associated with Investments: "*...the Task Force has replaced the GHG emissions associated with investments metric in the supplemental guidance for asset owners and asset managers with a weighted average carbon intensity metric. The Task Force believes the weighted average carbon intensity metric, which measures exposure to carbon-intensive companies, addresses many of the concerns raised*".

2 As is standard practice in environmental analysis, carbon emissions are used as a proxy for the different GHG emissions, which include, in addition to water vapour (H_2O) and carbon dioxide (CO_2), mainly methane (CH_4), nitrous oxide (N_2O) and ozone (O_3).

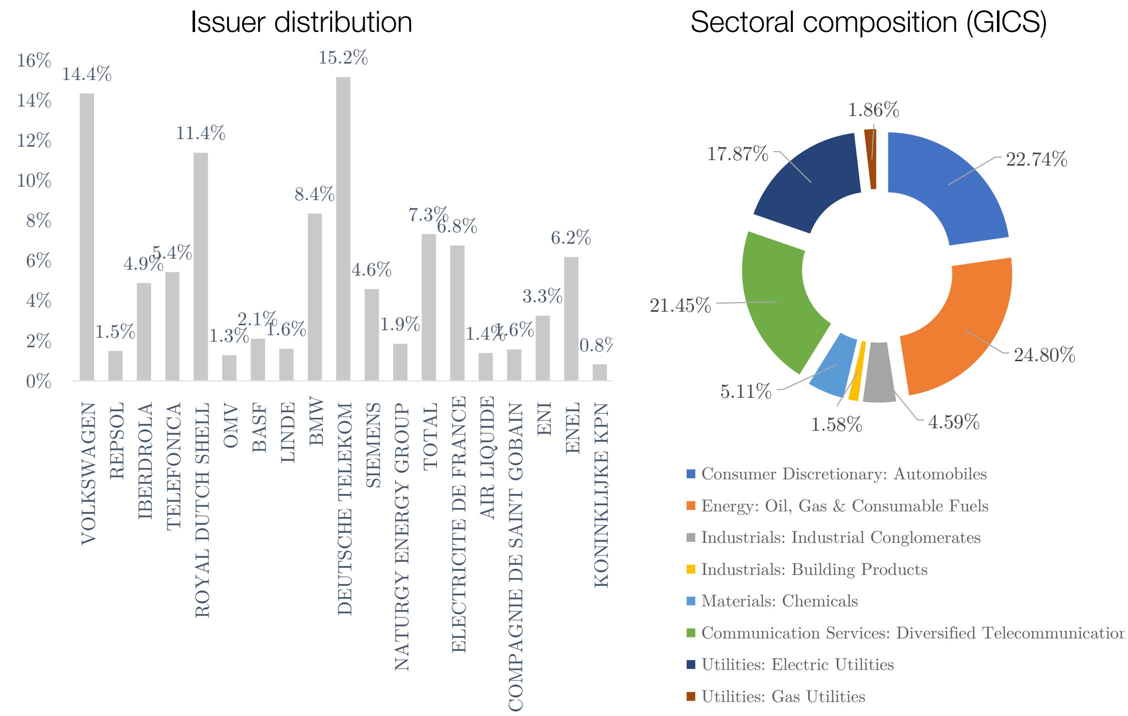
3 For simplicity, the latest available carbon intensity figure is used, acknowledging that this is a static metric and does not take into account issuers' "climate ambition", i.e., their efforts to reduce their emissions footprint over time. Future analysis could be enriched by introducing dynamic intensity metrics, incorporating both past achievements on the decarbonisation trajectory and future emission reduction plans by companies.

Table 1. Benchmark portfolio: Key characteristics

Company	Country	GICS sector	GICS industry	Long-term debt (€ m)	Carbon intensity (tCO_2e/sales)
VOLKSWAGEN	Germany	Consumer Discretionary	Automobiles	114,809	32.0
REPSOL	Spain	Energy	Oil, Gas & Consumable Fuels	11,978	673.0
IBERDROLA	Spain	Utilities	Electric Utilities	39,148	449.4
TELEFONICA	Spain	Communication Services	Diversified Telecommunication	43,464	17.3
ROYAL DUTCH SHELL	Netherlands	Energy	Oil, Gas & Consumable Fuels	91,115	409.9
OMV	Austria	Energy	Oil, Gas & Consumable Fuels	10,348	664.6
BASF	Germany	Materials	Chemicals	16,845	353.1
LINDE	Germany	Materials	Chemicals	12,821	1,519.4
BMW	Germany	Consumer Discretionary	Automobiles	66,835	19.1
DEUTSCHE TELEKOM	Germany	Communication Services	Diversified Telecommunication	121,285	50.0
SIEMENS	Germany	Industrials	Industrial Conglomerates	36,687	22.0
NATURGY ENERGY GROUP	Spain	Utilities	Gas Utilities	14,826	1,007.2
TOTAL	France	Energy	Oil, Gas & Consumable Fuels	58,588	325.8
ELECTRICITE DE FRANCE	France	Utilities	Electric Utilities	54,066	405.8
AIR LIQUIDE	France	Materials	Chemicals	11,190	1,341.0
SAINT- GOBAIN	France	Industrials	Building Products	12,621	272.8
ENI	Italy	Energy	Oil, Gas & Consumable Fuels	26,064	875.0
ENEL	Italy	Utilities	Electric Utilities	49,519	745.6
KONINKLIJKE KPN	Netherlands	Communication Services	Diversified Telecommunication	6,608	55.0
WACI Benchmark portfolio					**303.4**

Source: Devised by authors. 2020 data from Bloomberg and companies' annual accounts and sustainability reports. Carbon intensity is measured as average emissions (metric tonnes of carbon dioxide or CO_2) divided by annual sales (millions of euro). Scope 1 and 2 emissions are included. Long-term debt includes all types of financial debt with a maturity greater than one year.

Chart 1. Benchmark composition



3.2 Sample representativeness and euro area investment-grade corporate debt market

When searching for candidate companies to be included in the benchmark portfolio, we looked for euro area large companies:

- with an investment grade rating, from different countries and sectors/industries;

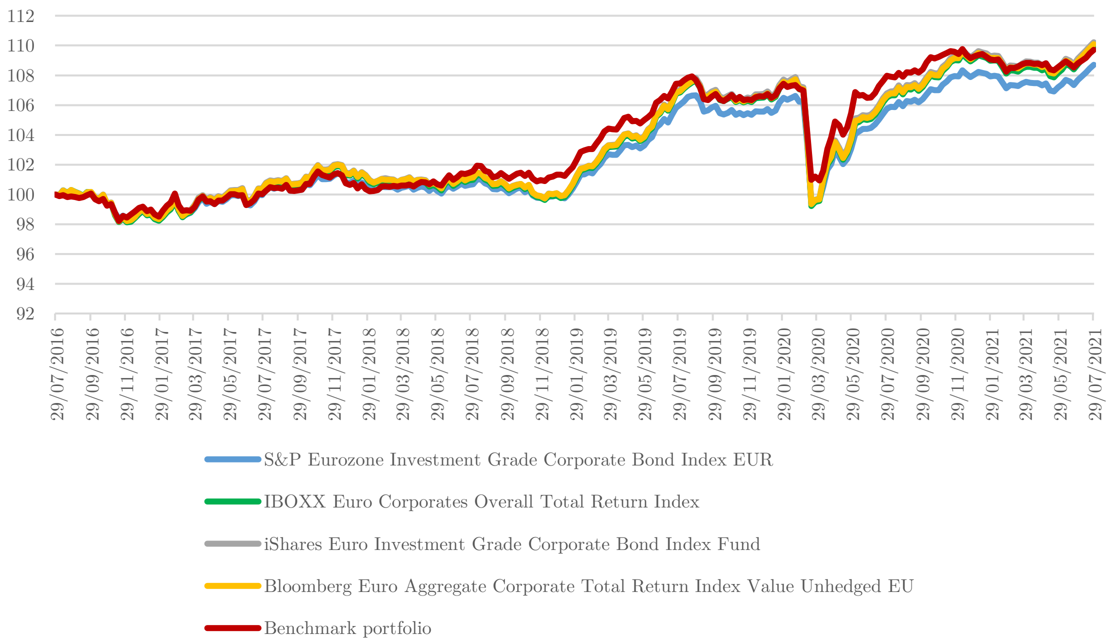
- with carbon footprint figures (scope 1 and 2) published for the financial year 2020;

- with available complete time series of quoted 5-year par rates; and

- that would generate a portfolio representative of the general market behaviour of the euro area investment-grade corporate debt market when weighted by outstanding debt (selected market criteria).

Chart 2 shows the market performance (base 100) of the selected portfolio against three market benchmark indices (S&P Eurozone Investment Grade Corporate Bond Index, Bloomberg Euro Aggregate Corporate Total Index Value and IBOXX Euro Corporates Overall Total Return Index) as well as the iShares Euro Investment Grade Corporate Bond Index Fund ETF. As can be observed in the chart, they all behave very similarly, with a cumulative return at the end of the sample period of around 10%, and sample correlations of weekly returns between the benchmark portfolio and market indices (some of them with more than 3,200 instruments) of 96% in the four cases. Thus, the selected issuers constitute a highly representative sample of the main indices of the euro area corporate bond market while satisfying the characteristic of maintaining a constant duration throughout the sample period.

Chart 2. Benchmark portfolio vs. euro area IG Corporate Bond Indices



3.3 Construction of historical return series

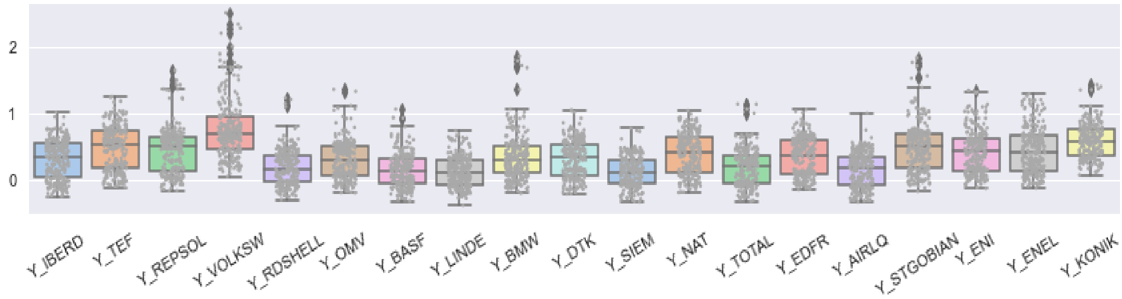
To isolate the analysis from different financial risk factors not directly linked to sustainability that could affect the conclusions, such as interest rate risk, credit risk, or foreign exchange risk, the initial portfolio was constructed with euro-denominated investment-grade issues, maintaining their duration (and maturity) so that they are constant[4] throughout the sample

[4] The maturity is constant over five years, the duration fluctuates weekly following changes in the internal rate of return, but always yields values very close to 5.

period. Achieving this does not come without cost; this requirement means not being able to use specific market issues (by ISIN), as it is precisely these characteristics of duration, maturity, etc. that vary over time. To overcome this difficulty, we use five-year par rates for the bonds of the different issuers, constructed from real market quotes and taken weekly from July 2016 to July 2021, thus covering a total sample period of five years (262 observations of yields per issuer).[5] Charts 3 and 4 show the evolution over time and a boxplot of the yields of the benchmark portfolio securities.

Chart 3. 5-year corporate bond yields

Chart 4. 5-year corporate bond yields boxplot



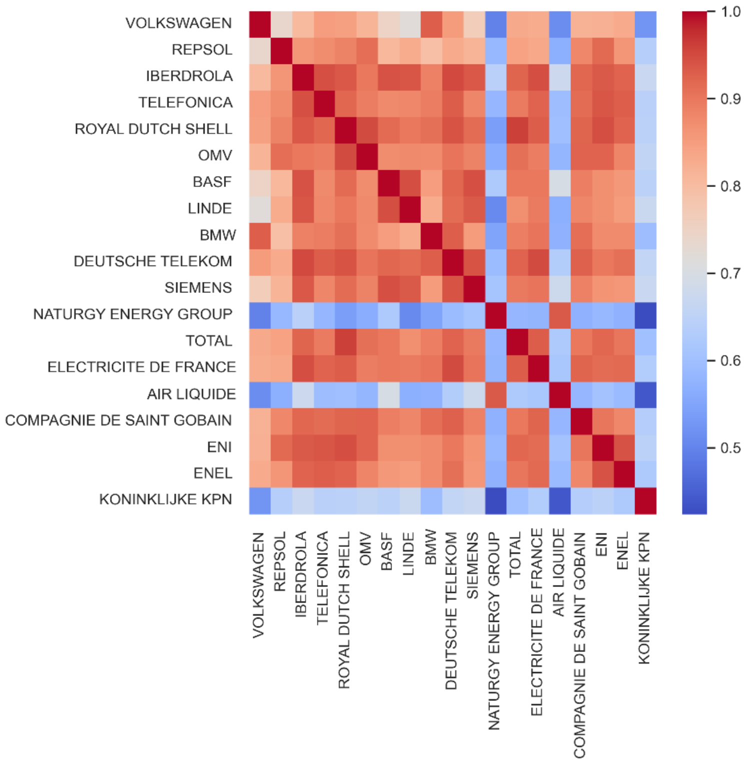
From these weekly market yields, we estimate the time series of company bond returns following a second-order Taylor approximation, as shown in equation (1), whereby the total return of a fixed income asset can be broken down into the sum of the carry of the position (coupon plus pull-to-par) and the market effect, as measured by the vector of key rate durations (KRD)*,* convexity and yield variations.

[5] For bullet bonds without optionality, the periodic return calculation is practically the same**,** taking clean prices plus accrued coupon, as approximating it by a second-degree Taylor expansion used in this paper. The big difference is that when calculating returns via prices, the bond's duration shortens over time, something that does not occur if par rates are used, allowing the duration of the portfolio to be kept constant over time, which is precisely the objective of the authors. What implicitly underlies is a periodic rebalancing process whereby the bond whose duration has shortened is sold and the new bond issued at par (5Y on-the-run) is purchased. It should be borne in mind that the par rates used in this study are constructed from real bond prices quoted on the market.

Table 2. Basic bond statistics: return, volatility and Sharpe ratio.

ISSUERS	Annualised return	Annualised volatility	Sharpe ratio
VOLKSWAGEN	3.57%	3.96%	0.903
REPSOL	2.55%	2.90%	0.880
IBERDROLA	1.67%	2.66%	0.627
TELEFONICA	2.42%	2.77%	0.872
ROYAL DUTCH SHELL	1.08%	2.88%	0.374
OMV	1.65%	2.78%	0.594
BASF	1.02%	2.79%	0.364
LINDE	0.84%	2.38%	0.352
BMW	1.78%	3.47%	0.513
DEUTSCHE TELEKOM	1.59%	2.49%	0.640
SIEMENS	0.78%	2.34%	0.333
NATURGY ENERGY GROUP	1.97%	4.28%	0.460
TOTAL	1.09%	2.71%	0.401
ELECTRICITE DE FRANCE	1.72%	2.48%	0.694
AIR LIQUIDE	0.94%	3.95%	0.238
COMPAGNIE DE SAINT GOBAIN	2.68%	3.03%	0.885
ENI	2.18%	2.92%	0.745
ENEL	2.13%	2.82%	0.756
KONINKLIJKE KPN	2.74%	2.77%	0.988

Chart 5. Correlation heat map between asset returns in the benchmark portfolio



$$(1)\quad R_t^{T,i} = y_{t,m}^{T}\mathrm{dt} - \sum_{m=1}^{M} \mathrm{KRD}_{t-1,m}^{i} \cdot \Delta y_{t,m}^{T} + \frac{1}{2} \cdot CVX_t^{i} \cdot \left(\Delta y_{t,m}^{i}\right)^2 \cdot 100$$

Once the weight vector '*b*' and the return series are obtained, we can calculate the main benchmark metrics as well as their market value over time. Table 2 shows the average annualised return, volatility and Sharpe ratio of the different assets.

As can be seen in Chart 5, correlations are relatively high across issuers. This is precisely due to the control mechanism imposed on the different risk factors: bonds in the benchmark portfolio correspond to the same asset class, corporate debt issued in the same currency, with the same duration and investment-grade rating.

4 In search of the cost of decarbonising the portfolio

4.1 Construction of the SRI Efficient Frontier

In the same line of work as Pedersen et al. (2021) for equity assets, and starting from three variables (risk, return and a third variable representing the degree of 'sustainability'), we reduce the problem of the sustainability-concerned investor to the optimisation of two variables in the set of investment opportunities: a climate risk variable, represented by portfolio carbon intensity, and a financial variable, namely the deviation in terms of TE from the benchmark given that it is an investor with a passive management mandate. In their study, Pedersen et al. use the ESG score as an extra-financial variable and the Sharpe ratio as a financial variable.

The efficient frontier thus designed ('SRI Efficient Frontier') is a function solely of the assets' characteristics (carbon intensity, risk and return) and does not depend on the investor's preferences, thus fulfilling the principle of separation of the traditional mean-variance frontier. Likewise, as a result of the optimisation of TE and WACI, the efficient frontier is decreasing and convex, while the one derived in Pedersen et al. from the Sharpe-ESG score optimisation is decreasing and concave.

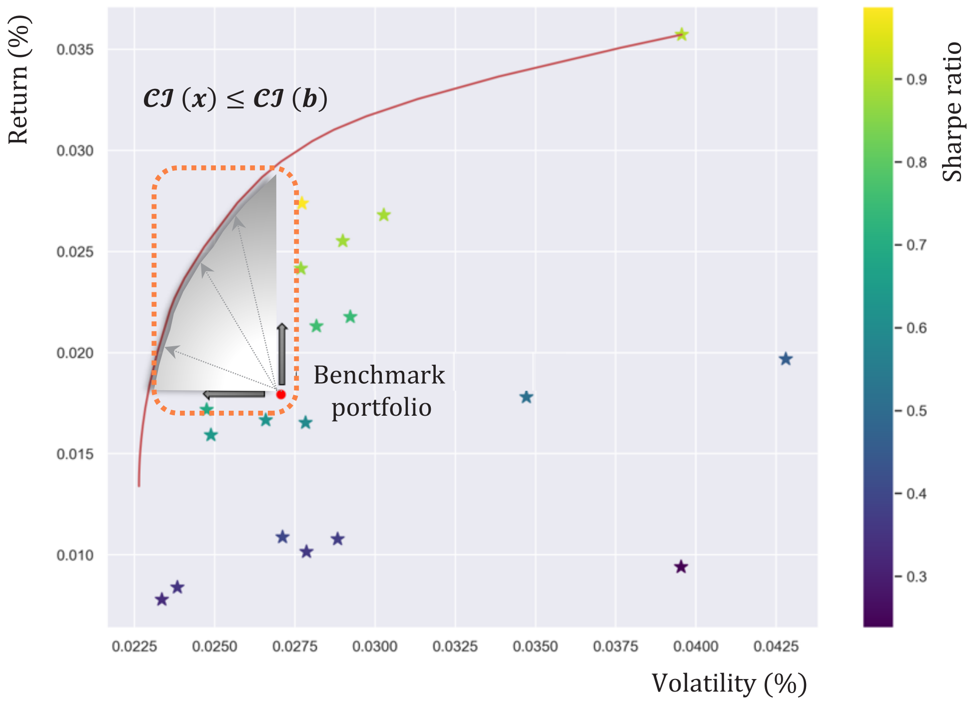
Chart 6 shows, in the risk-return space, the pairs of different assets, the benchmark portfolio '*b*' and the Markowitz efficient frontier. The benchmark portfolio*,* constructed on market criteria, is not efficient from a mean-variance optimisation perspective, i.e., it is possible to find portfolios with lower volatility for a given level of return, or vice versa.

The goal of this section is to find the cost of decarbonising the investment portfolio '*b*', i.e., the cost of reducing the carbon footprint (WACI) of the initial investment position by varying the different weights assigned to the companies.

Thus, the aim is to find the vector of weights that generates optimal decarbonised portfolios in the sense that they achieve the reduction in the initial carbon footprint of the benchmark portfolio*,* $\mathcal{CI}\,(x) \leq \mathcal{CI}\,(\mathrm{b})$, while complying with other restrictions on its financial variables.

The approach underlying the analysis we have carried out is to seek the optimal reallocation of assets within a passive management mandate, where the preferred or structural position is that of the benchmark portfolio, both in terms of its sectoral distribution and its asset composition. In passive portfolio management, the manager's fundamental objective is to minimise the active risk assumed against the benchmark portfolio, thus requiring a high degree of indexation in the assumed positions. TE, defined as the volatility of active returns (excess return between the portfolio and the benchmark), is usually used as a metric for this active risk.

Chart 6. Mean-variance efficient frontier, individual assets and benchmark portfolio



Therefore, with the dual objective of fulfilling a passive management mandate and decarbonising the portfolio, the problem lies in calculating the efficient frontier, consisting of the set of optimal portfolios (x^*) that minimise TE for each level of carbon intensity ($\mathcal{CI}$), namely, we search for the set of portfolios that reduces the initial WACI with the smallest deviation from the reference portfolio in terms of TE. Subsequently, we examine the relationship between the financial variables and the green variables; under this approach, portfolio's return and risk metrics (volatility, VaR, MaxDD, etc.) are variables resulting from the optimisation process and not direct constraints incorporated into the exercise.

The new portfolio, which differs from the benchmark in its asset composition and weighting, is characterised by a weight vector '*x*' different from vector '*b*'.

$x\ = (x_1\,, \dots, x_n\,) =$ weight vector of portfolio '*x*'.

The excess return ('e') and the ex ante TE of portfolio '*x*' versus portfolio '*b*' are then defined as:

$$e = \ R(x) - R(b) = \sum_{i=1}^{n} x_i\ R_i - \sum_{i=1}^{n} b_i\ R_i\ = \mu\,(x \mid b) = (x-b)^T\ R$$

$$TE\ = \ \sigma(x \mid b) = \ \sigma(e) = \ \sqrt{(x-b)^T\ \Sigma\ (x-b)}$$

In the quadratic optimisation programme to be solved, two constraints are imposed: full portfolio investment and the prohibition to take short positions (no short selling).

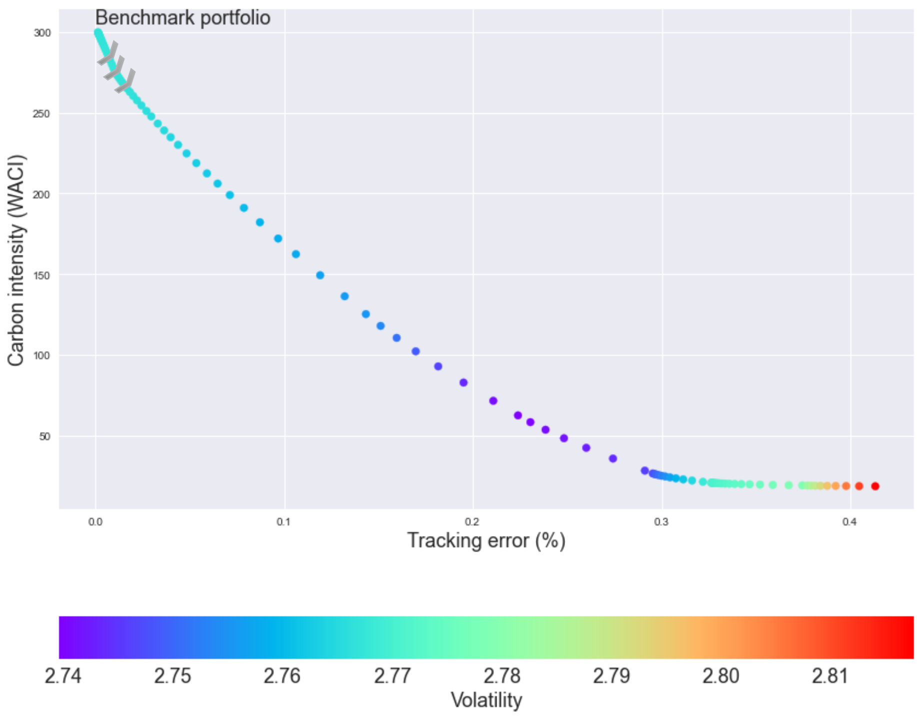
$$x^*(\gamma) = arg\,min \frac{1}{2}\ (x-b)^T\ \Sigma\ (x-b) - \gamma\ \mathcal{CI}\ (x)$$

$$s.t.\ \begin{cases} 0_n \le x \le 1_n \\ 1_n^T x = 1 \end{cases}$$

Where 'γ' is the parameter representing the desired degree of portfolio decarbonisation. If $\gamma = 0$ the problem represents only the passive management objective of minimising TE; conversely, if $\gamma = \infty$, the optimisation problem is equivalent to minimising the carbon intensity of the portfolio.

Chart 7 presents the efficient frontier resulting from the optimisation exercise, showing that a well-defined trade-off between the reduction in the portfolio's carbon footprint and TE indeed exists. This function is convex and has a negative slope so that a reduction in the carbon footprint requires an increasing TE against the benchmark portfolio. In other words, the decarbonisation objective involves assuming a higher cost in terms of risk deviation against the benchmark portfolio.

Chart 7. Efficient frontier: carbon intensity (WACI) vs. tracking error (TE)



4.2 The costs of portfolio decarbonisation

As shown in the previous section, in a passive portfolio management context, investors aiming to implement portfolio decarbonisation strategies must accept a certain level of active risk. This cost has to be estimated as a precondition for achieving a realistic carbon footprint reduction in line with the parameters of the investment mandate to which the portfolio is subject.

The results of this analysis appear consistent with the conclusions reached in other research studies applied to fixed income portfolios, such as Ben Slimane et al. (2020), which also find an inverse trade-off between the decarbonisation metric (in their case the ESG score of each company) and the ex post TE of the portfolio against the benchmark.

Chart 8 and Table 3 show the relationship between the efficient portfolios and risk and return metrics.[6]

Chart 8. Percentage reduction in carbon footprint vs. financial variables

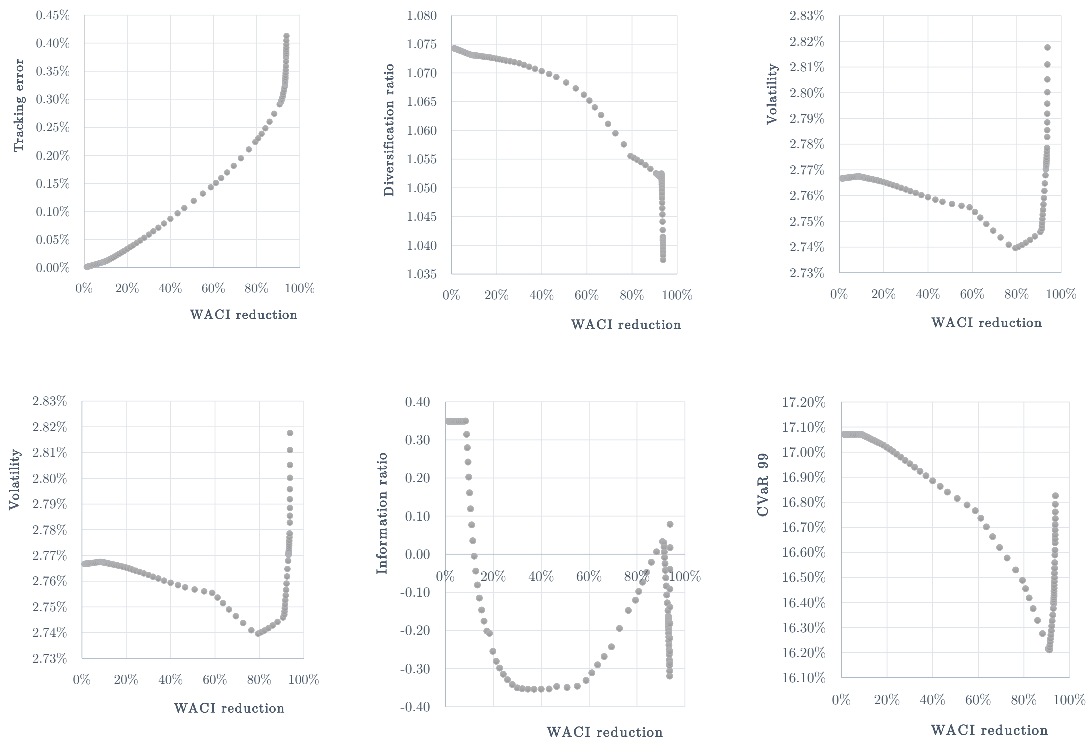


Table 3. Summary of metrics for the efficient frontier portfolios (TE-WACI)

Portfolio	TE	WACI	Δ% WACI	Volatility	Return	Excess return	Sharpe ratio	Information ratio	CVaR	MaxDD	DR	No of assets
1	0.001%	299.77	1.2%	2.767%	1.885%	0.000%	0.681	0.349	17.07%	6.59%	1.0743	19
10	0.004%	291.73	3.9%	2.767%	1.886%	0.002%	0.682	0.349	17.07%	6.59%	1.0739	19
20	0.011%	274.85	9.4%	2.767%	1.887%	0.003%	0.682	0.242	17.07%	6.59%	1.0731	18
30	0.022%	257.54	15.1%	2.766%	1.881%	-0.003%	0.680	-0.147	17.04%	6.59%	1.0728	18
40	0.059%	212.34	30.0%	2.762%	1.864%	-0.021%	0.675	-0.351	16.95%	6.60%	1.0717	16
50	0.151%	117.97	61.1%	2.754%	1.837%	-0.047%	0.667	-0.311	16.74%	6.56%	1.0652	14
60	0.260%	42.50	86.0%	2.743%	1.879%	-0.005%	0.685	-0.021	16.33%	6.34%	1.0540	7
70	0.308%	23.63	92.2%	2.759%	1.859%	-0.026%	0.674	-0.083	16.31%	6.42%	1.0521	6
80	0.330%	20.56	93.2%	2.771%	1.819%	-0.066%	0.656	-0.199	16.44%	6.53%	1.0506	4
90	0.375%	19.20	93.7%	2.778%	1.765%	-0.120%	0.635	-0.320	16.61%	6.60%	1.0415	4
100	0.413%	18.71	93.8%	2.818%	1.917%	0.032%	0.680	0.079	16.83%	6.61%	1.0375	3

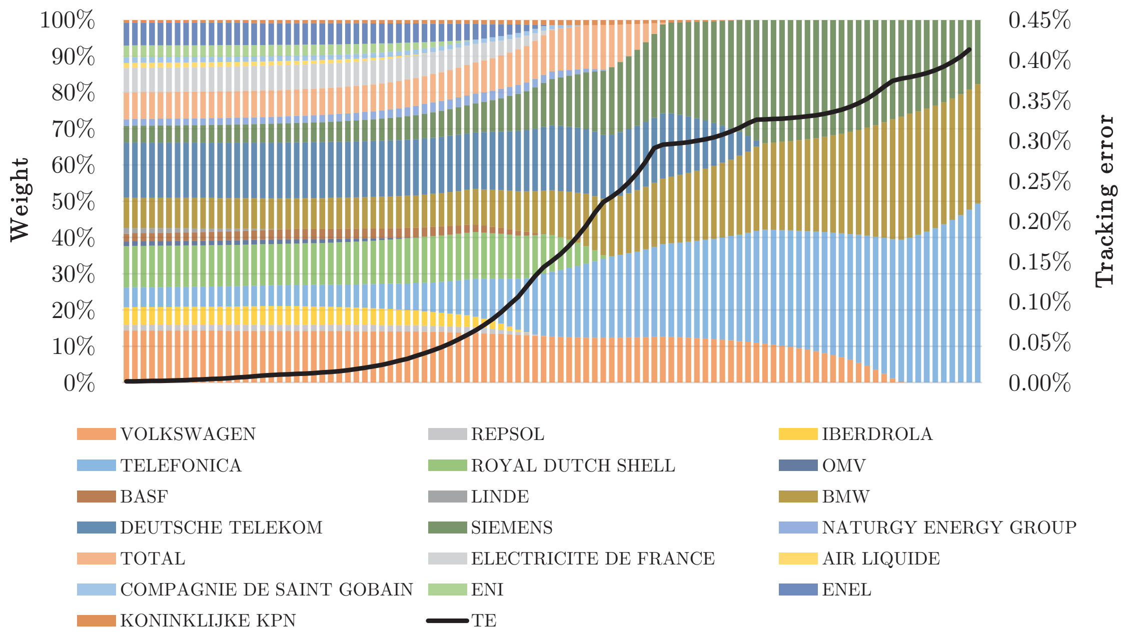
Chart 9 shows the different asset compositions of the optimal portfolios along the efficient frontier in terms of TE and WACI. The increase in active risk is also reflected in a reduction

[6] CVaR is the historical expected shortfall at 99%, MaxDD is the maximum drawdown suffered by the portfolio during the analysed period, DR is the diversification ratio Choueifaty and Coignard (2008) calculated as the ratio between the weighted average of the asset volatilities and the portfolio volatility. The higher the ratio, the greater the diversification achieved by the portfolio since the correlation between assets is lower.

$$\mathrm{DR}(\mathrm{x}) = \frac{\sum_{i=1}^{n} x_i \sigma_i}{\sigma(x)} = \frac{x^T \sigma}{\sqrt{x^T \sigma\, x}}$$

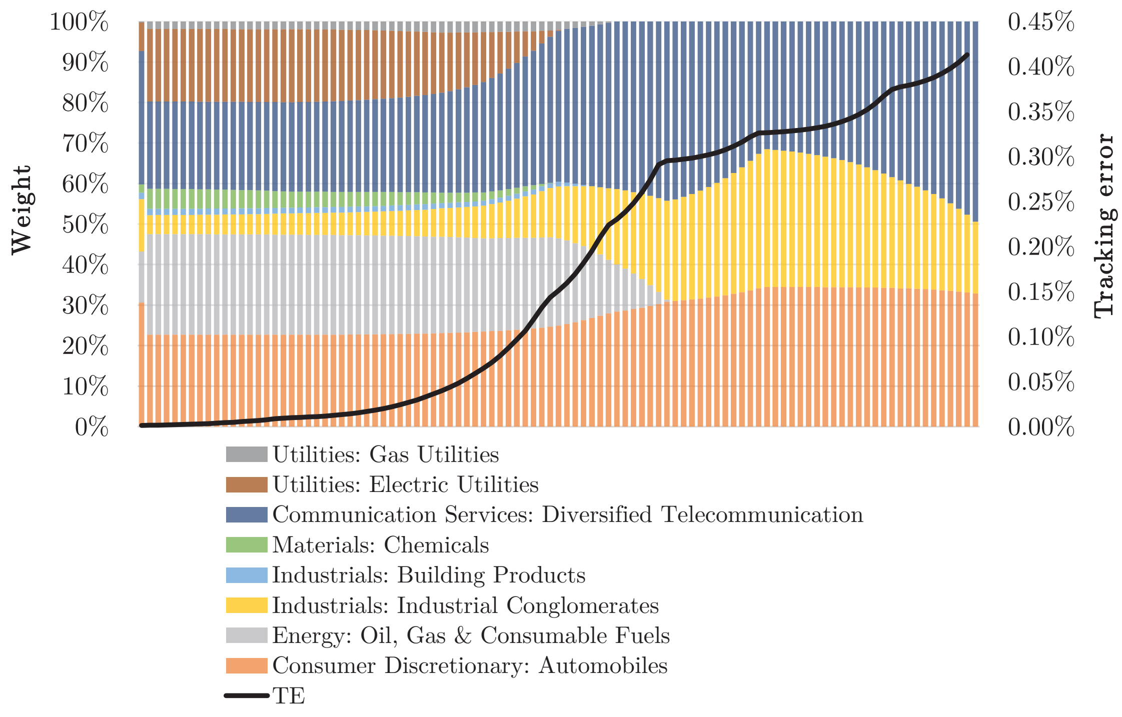
in the number of assets employed, from the initial portfolio composition '*b*' (TE_{min} = 0) to the position where investment is concentrated in only three companies (TE_{max} = 0.41%).

Chart 9. Asset composition of the TE-WACI efficient frontier portfolios



The same conclusion can be observed if this fact is analysed from a sectoral concentration perspective.[7] As can be seen in Chart 10, once a certain level of carbon footprint reduction is achieved, at the cost of increasing TE, further decarbonisation is accompanied by higher sectoral concentration compared with the initial portfolio.

Chart 10. Sectoral composition of the TE-WACI efficient frontier portfolios



[7] The GICS sector and industry classification has been used for the individual issuers.

Thus, the sustainability goal also has to be viewed from a diversification perspective, assuming that portfolio decarbonisation entails an increasing cost in terms of:

- a loss of efficiency in diversification, as the number of assets decreases, and
- a higher degree of sectoral concentration, which could contravene the portfolio management mandate.

The last section of the paper will apply SRI strategies that allow managing this cost in terms of diversification by maintaining a sectoral composition similar to that of the benchmark to achieve the portfolio's decarbonisation target.

Finally, it is important to note that, based on the benchmark portfolio, the decarbonisation objective or reduction in the carbon footprint can be achieved while improving efficiency in terms of risk and return. This is due to two facts:

- First, the benchmark is a portfolio constructed under market criteria, not through a mean-variance optimisation programme; therefore, as seen above, portfolio '*b*' falls below the Markowitz efficient frontier.

- Second, there seems to be some positive correlation between the carbon footprint of the issuer and the volatility of returns, such that, at the start of the decarbonisation process, the weight assigned to greener and less volatile issuers increases in the universe of assets (see Chart 11).[8] However, as the process progresses and the number of assets diminishes (see Chart 12), the DR falls and results in a spike in portfolio volatility.

Chart 11. Portfolio volatility, weighted average volatility and reduction in WACI

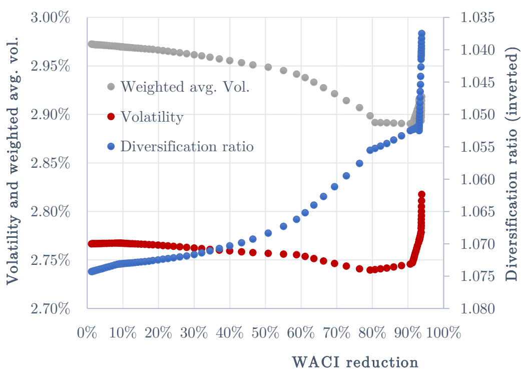
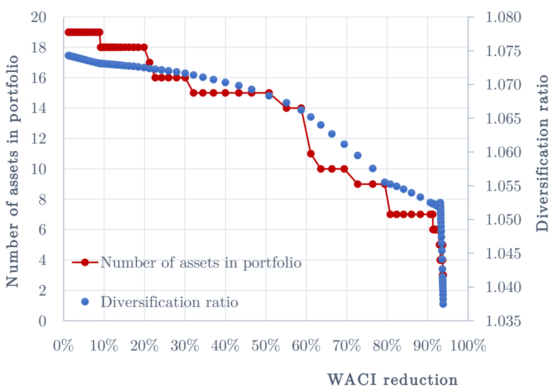


Chart 12. Number of assets and reduction in WACI and DR



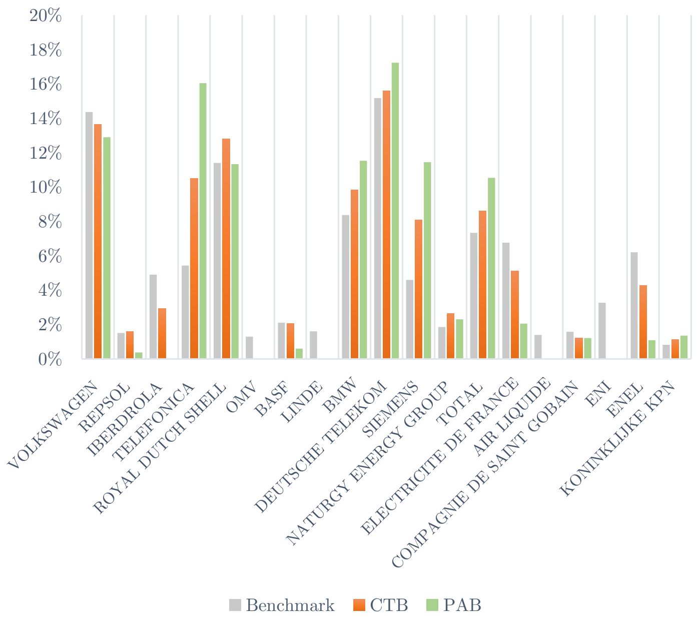
Ultimately, sustainability-minded investors will need to choose the desired degree of reduction in the portfolio's carbon footprint and be aware of the cost associated with that level of decarbonisation. In the case of European investors, if their objective is to meet the minimum transition risk standards dictated by the Paris Agreement commitments, in line

[8] By mentioning this positive relationship found in the sample between the issuer's WACI reduction and the volatility of its bonds, we point to a mere casual, rather than causal, correlation. The analysis of the relationship between the temporal dynamics of an issuer's carbon footprint and the return/volatility of its securities is left for a future analysis and is beyond the scope of this study.

with the climate benchmarks set out in EU regulation (climate transition benchmarks (CTB) and Paris-aligned benchmarks (PAB)), they will need to aim for an initial 30% (CTB) or 50% (PAB) reduction in the portfolio's carbon footprint relative to their investment universe.[9]

For illustrative purposes, Chart 13 presents the optimal composition of the portfolios that achieve such a reduction in the carbon footprint and, at the same time, minimise the TE against the benchmark. Table 4 shows the main metrics comparing the benchmark portfolio with the two portfolios fulfilling the initial decarbonisation required by the CTB and PAB.

Chart 13. Asset composition of the benchmark, CTB and PAB portfolios.



As illustrated in Table 4, both portfolios entail a deviation in terms of TE from the benchmark, increasing with the degree of required decarbonisation: 6 basis points (bp) of TE for the CTB portfolio (-30% WACI) and 12 bp of TE for the PAB portfolio (-50% WACI). However, the impact on risk-return metrics is limited, with a slight decrease in the Sharpe ratio, especially for the PAB portfolio (as mentioned above due to the high correlation between the assets in the portfolio).

Table 4. Portfolios complying with the CTB and PAB: summary metrics

Portfolio	TE	WACI	Δ% WACI	Volatility	Return	Excess return	Sharpe ratio	Information ratio	CVaR	MaxDD	DR	No of assets
Benchmark	-	303.4	-	2.77%	1.88%	-	0.678	-	17.07%	6.59%	1.074	19
CTB	0.059%	212.3	30%	2.76%	1.86%	-0.021%	0.675	-0.351	16.95%	6.60%	1.072	16
PAB	0.119%	149.3	50%	2.76%	1.84%	-0.042%	0.668	-0.350	16.81%	6.60%	1.065	15

4.3 Relaxing the long-only restriction

As a final note in this section, we study the introduction of short positions in the portfolio composition. Within the restrictions established in the optimisation programme we have imposed that portfolio weights must be greater than or equal to zero for all assets, thus

[9] See the final report of the EU Technical Expert Group on Sustainable Finance (TEG). For simplicity, only the initial 30% and 50% reduction in carbon footprint against the baseline portfolio is illustrated. EU standards also dictate an additional decarbonisation trajectory of 7% on average per year, along with other exclusion requirements for certain activities and companies.

focusing on long-only investors, which is indeed a real restriction for many institutional investors such as most investment funds or pension plans. However, this may not be a restriction for certain types of institutional investors, e.g., hedge funds, where short positions on issuers are allowed and might be obtained through derivatives. Thus, we now examine how the performance of long-only investors and those who are not subject to this restriction can be affected throughout the portfolio decarbonisation process, which provides a better understanding of climate performance within the framework of portfolio management and is a novel contribution.

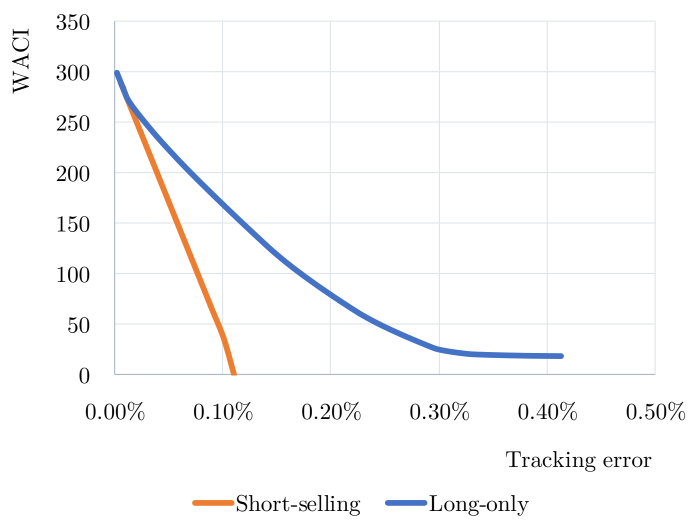
Therefore, the restrictions in the optimisation programme are modified in such a way that weights between -1 and 1 are allowed, and that the minimum WACI of the portfolio is zero in order not to obtain portfolios with negative carbon intensities.

$$x^*(\gamma) = arg\,min \frac{1}{2}\,(x-b)^T\,\Sigma\,(x-b) - \gamma\,CI\,(x)$$

$$s.t.\ \begin{cases} -1_n \leq x \leq 1_n \\ \sum_{i=1}^{n} x_i\,CI_i \geq 0 \end{cases}$$

Chart 14 shows the inverse relationship between WACI and TE for long-only and short-selling investment strategies. In the case of the investor being able to adopt short positions in the portfolio, the trade-off becomes a linear function with a greater slope than the efficient frontier of the traditional investor, who progressively assumes a higher cost in terms of TE per unit of WACI reduction. Thus, the possibility of adopting short positions results in a lower cost for the short-selling strategy in terms of active risk, which is lower the higher the decarbonisation objective is. This long-short differential in terms of TE is measured via the horizontal distance between the two curves. This result is in line with traditional portfolio management theory, which anticipates that when the investor is allowed to assume short positions, the efficient frontier widens, allowing a larger set of investment possibilities, while improving the trade-off between risk and return.

Chart 14. Efficient Frontier: carbon footprint (WACI) vs. tracking error (TE) when short-selling is allowed



5 Strategies for SRI management

5.1 The toolkit of SRI strategies in fixed income

As discussed in the previous section, the fixed income portfolio decarbonisation process may require certain costs in terms of reduced diversification, increased sectoral concentration and higher active risk against the benchmark portfolio. These costs, together with a potential impact on performance metrics, could have negative consequences for the investor's objectives in a passive management context.

To overcome this drawback, fixed income investors have several strategies at their disposal that should allow them to integrate SRI factors into the management of their investment portfolios, in order to meet both their objectives and the investment mandate. These strategies, broadly used in equity portfolios, are not mutually exclusive and can be efficiently combined to enable the incorporation of these criteria into the fixed income investment process.

In this paper, we will use four strategies for the portfolio design, namely, exclusion strategy, best-in-class*,* tilting*,* and Green-Parity*,* to empirically analyse how the application of these green strategies impacts the achievement of the decarbonisation goal and the risk-return metrics versus the market benchmark.[10] The basic characteristics of the strategies and the key factors to be taken into account in their implementation are described below.

An important consideration when implementing these strategies in a bond portfolio, especially in negative screening or best-in-class approaches, is that they can significantly reduce the eligible universe, making it difficult to implement such strategies efficiently.

5.1.1 Exclusion strategy (negative screening)

This strategy seeks to exclude from the investment universe certain issuers operating in sectors, products or services that are considered unacceptable according to the investor's ethical principles or values. In the case of an investor concerned about climate risk, the most polluting issuers or sectors would be eliminated. The application of this strategy entails, in most cases, the reduction of the eligible universe, as well as the need to adequately define and maintain the exclusion criteria. Under this approach, a maximum acceptable threshold is set ex ante in terms of carbon intensity ($\mathcal{CI}^*$) and the most polluting issuers (those with a $\mathcal{CI}_i$ above $\mathcal{CI}^*$) are eliminated from the universe of eligible assets. Let us assume that the threshold $\mathcal{CI}^*$ is set at 700 tCO_2e/sales, which excludes five issuers from the initial universe (19% of those in the benchmark portfolio*)*. Of course, the results will depend on the $\mathcal{CI}$ threshold chosen. In this case, a high threshold has been preferred to maintain a sectoral composition similar to the benchmark.

5.1.2. Best-in-class strategy

Best-in-class is a variant of positive screening strategies and consists of actively filtering companies according to their position in a ranking based on the chosen SRI metric, in this case, the carbon intensity of each issuer $\mathcal{CI}_i$. In the example, the issuer with the lowest carbon intensity is selected from each sector. This issuer's weighting in the strategy will be

[10] Other SRI strategies are increasingly being applied in the fixed income world, such as: (i) thematic or impact investing, which seeks to actively direct investment towards an explicit environmental impact objective, for example, by constructing a green bond portfolio; (ii) engagement, which uses the investor's influence to try to steer the issuer's SRI factors and risk exposure and/or increase its transparency to the market on these aspects; and (iii) integration, which attempts to holistically incorporate extra-financial information and SRI considerations, both qualitatively and quantitatively, into the investment process and management decisions.

its sectoral weight in the benchmark portfolio. In short, the goal is to select the leaders within each sector based on this metric, maintaining the same sectoral composition as the benchmark.

5.1.3. Tilting strategy

This approach is also a variant of positive screening. In this case, the portfolio is constructed by applying a weighting factor 'tf_i ' (tilting factor) to the initial issuer weighting in the benchmark portfolio, so that the issuer weight '*i*' in portfolio '*p*' is defined as:

$$w_i^p = (1 + tf_i)\ w_i^b$$

where:

w_i^p = issuer weighting '*i*' in portfolio '*p*' (tilting strategy)
w_i^b = issuer weighting '*i*' in benchmark portfolio

by increasing or decreasing, relative to the *benchmark*, its weight in the strategy by a factor of (1+tf_i), depending on its carbon intensity.

The sample is divided into quantiles and the issuers are ranked according to their carbon intensity. In the example, tertiles are used: '1' for issuers with low intensity, '2' for medium intensity, and '3' for high intensity. The factor 'tf_i ' is defined according to the following scheme:

$$tilting\ factor\ (tf_i) = \begin{cases} 1 & \text{first tertile (low } \mathcal{CI}\text{)} \\ -0.33 & \text{second tertile (medium } \mathcal{CI}\text{)} \\ -0.67 & \text{third tertile (high } \mathcal{CI}\text{)} \end{cases}$$

Thus, bonds from issuers with a low $\mathcal{CI}_i$ will be included in the portfolio with a weight equal to the benchmark weight (tf_i = 1), penalising, versus their neutral weight*,* those issuers that have medium $\mathcal{CI}_i$ (tf_i = -0.33) and, to a greater extent, issuers with a high $\mathcal{CI}_i$ (tf_i = -0.67).[11]

5.1.4. Green-Parity strategy

We define Green-Parity as an SRI strategy that sets the optimal weighting so that each of the portfolio's assets generates the same climate risk budget, i.e., each issuer equally contributes to the portfolio WACI, such that:

$$w_i\,\mathcal{CI}_i = w_j\,\mathcal{CI}_j \quad \forall\ i \neq j$$

$$\mathcal{CI}\ (w) = \sum_{i=1}^{n} w_i\ \mathcal{CI}_i = w^T\ \mathcal{CI}$$

Under this strategy, as in risk budgeting approaches,[12] risk (in this case, climate risk) is the main criterion for asset allocation, seeking to ensure that no component in the portfolio is

[11] See Schoenmaker (2021) for the application of this approach to the potential decarbonisation of the Eurosystem monetary policy.

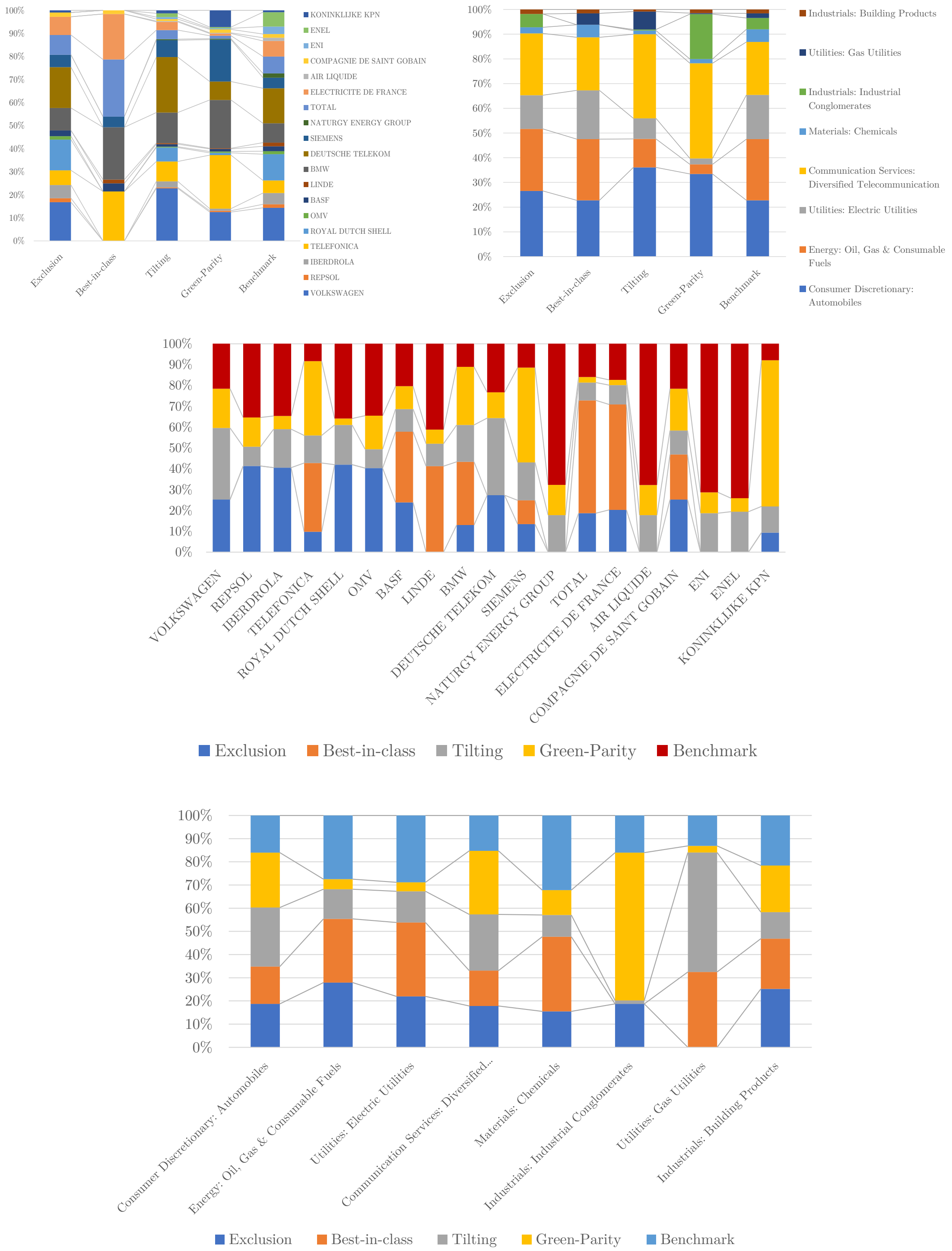
[12] Risk-budgeting encompasses a set of investment strategies in which asset allocation is based on risk-sharing. Among these strategies, the equal risk contribution (ERC) strategy stands out. This strategy seeks the asset weighting that equalises the contribution to total portfolio volatility (see Maillard, Roncalli and Teiletche (2010)). However, the nature of the climate risk metric (CI) differs from volatility, as the latter satisfies the sub-additive property: $\sigma(x) \leq \sum x_i \sigma_i$ due to correlation, while climate risk does not provide diversification gains.

more polluting than another, so that lower carbon intensity assets are over-weighted, and vice versa. Thus, issuer weightings in the portfolio are calculated by the inverse value of the $\mathcal{CI}_i$ as follows:

$$w_i = \frac{1/\mathcal{CI}_i}{\sum_{i=1}^{N}\left(\frac{1}{\mathcal{CI}_i}\right)}$$

Chart 15 shows the asset and sectoral composition for the four green strategies set against the benchmark, from a portfolio perspective, and the relative share of each issuer and sector within the different strategies.

Chart 15. Issuer and sectoral composition: strategies vs. benchmark



As mentioned in Section 1, sustainability-minded investors have different investment strategies at their disposal to achieve their decarbonisation goal without having to deviate significantly from their benchmark portfolio. Table 5 presents the results of applying the above-mentioned SRI strategies to the benchmark where, additionally and for comparison, the equal-weighted naive strategy is incorporated.

Table 5. Results of SRI strategies vs. benchmark portfolio

	EW	Exclusion	Best-in-class	Tilting	Green-Parity	Benchmark
WACI	**486.21**	**194.68**	**203.46**	**136.47**	**76.11**	**303.43**
Δ%WACI (vs. benchmark)	60.2%	-35.8%	-32.9%	-55.0%	-74.9%	-
Tracking error	0.42%	0.15%	0.27%	0.28%	0.28%	0.00%
Return	1.81%	1.89%	1.67%	2.07%	2.02%	1.88%
Volatility	2.65%	2.80%	2.73%	2.87%	2.76%	2.77%
Sharpe ratio	0.684	0.676	0.610	0.721	0.730	0.679
VaR	5.67%	5.81%	5.73%	5.99%	5.87%	5.73%
CVaR	16.51%	17.18%	17.31%	17.15%	16.54%	17.07%
MaxDD	6.75%	6.57%	6.72%	6.59%	6.33%	6.59%
Information ratio	-0.17	0.06	-0.78	0.67	0.47	-
Diversification ratio (DR)	1.122	1.056	1.053	1.060	1.078	1.073
Mean Squared Deviation (MSD)	0.41%	0.07%	0.00%	0.79%	1.60%	0.00%
Herfindahl index (HI)	16.34%	21.87%	19.65%	27.12%	29.59%	19.65%
Δ%WACI / TE	-1.42	2.46	1.20	1.96	2.63	-
Δ%WACI / HI	-3.69	1.64	1.68	2.03	2.53	-

As can be seen, all the resulting SRI portfolios reduce the carbon footprint compared with the benchmark. However, the equal-weighted portfolio does not manage to reduce the portfolio WACI, instead increasing it to 486.2 tCO_2e/sales (+60%). The dominant strategy, for the sample and period analysed, is Green-Parity, as it is the most efficient, in relative terms, when comparing the degree of decarbonisation achieved against the cost in terms of TE (WACI/TE) and diversification, both at sectoral (WACI/HI)[13] and asset level (it achieves the highest diversification ratio among the strategies). These green performance ratios would be the equivalent to the traditional risk-return ratios, where financial return is replaced by the $\mathcal{CI}$ reduction and the denominator, instead of volatility, is penalised by TE or by the deviation from the benchmark in sectoral composition.

Chart 16 shows, in the WACI-TE space, the result achieved by each strategy, as well as its position relative to the efficient frontier. The Green-Parity strategy dominates the rest by achieving the highest degree of decarbonisation for a given deviation in terms of TE. This result depends, logically, on the parameters chosen for the different strategies, i.e., the exclusion percentage, the distribution and weighting of quantiles in the case of tilting, and the number of leaders selected within each sector in the best-in-class strategy. When it comes to practical implementation, investors must properly calibrate the strategy parameters to reach a position in the WACI-TE space compatible with their financial and climate objectives.

Chart 17 shows, for each of the four strategies, the relationship between the carbon intensity per issuer and the weighting assigned by the corresponding strategy.

[13] The Herfindahl index is a measure of the degree of sectoral concentration of a given index or, in this case, investment portfolio. It is calculated as the sum of the squares of the percentage of each sector in the portfolio. A higher value for the indicator reflects a greater concentration.

Chart 16. WACI - TE efficient frontier and SRI strategies

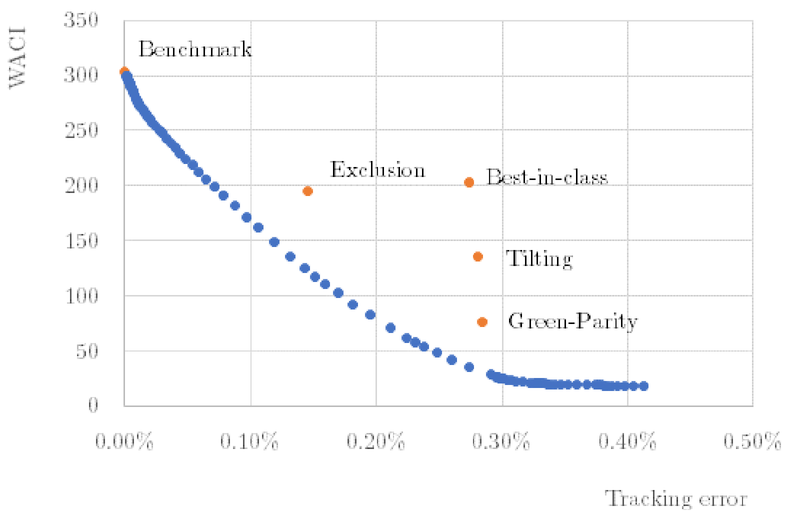
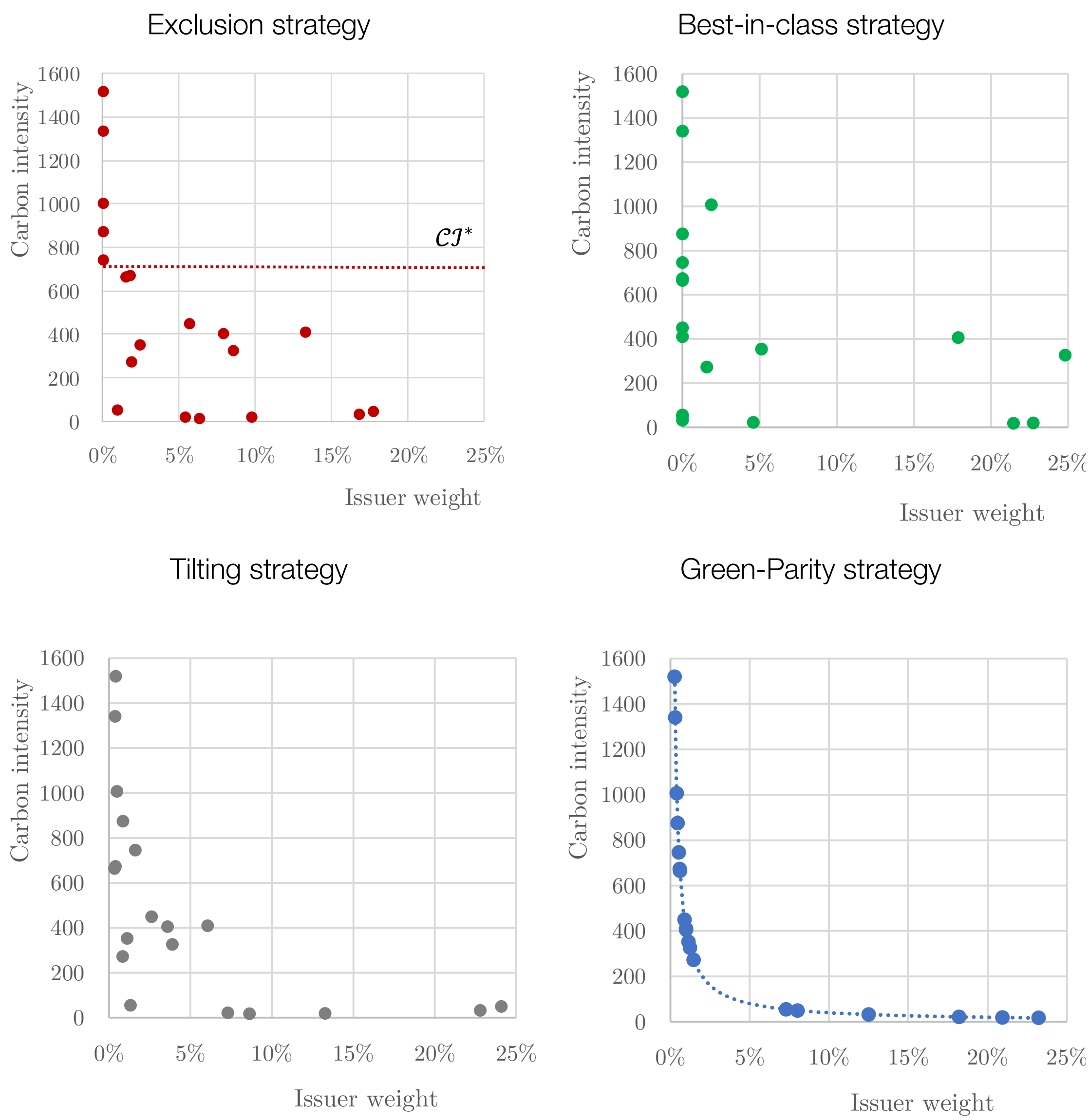


Chart 17. SRI strategies: CI by issuer and strategy weights

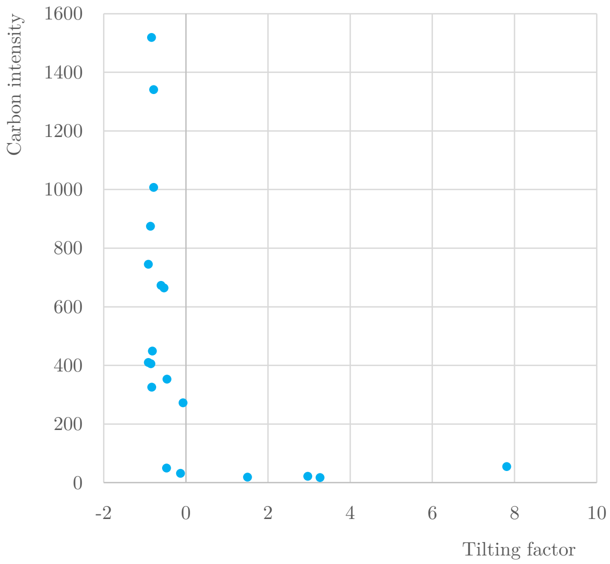


The new Green-Parity strategy can be understood as a particular case of the tilting strategy, where the partition number is the number of assets 'N', and the tilting factor applied to each asset is defined as:

$$tf_i = \frac{1/\mathcal{CI}_i}{w_i^b \left(\sum_{i=1}^{N} \left(\frac{1}{\mathcal{CI}_i} \right) \right)}$$

Chart 18 shows the set of tilting factors per issuer that makes the tilting strategy's weight vector equal to the one in the Green-Parity strategy.

Chart 18. Tilting factors corresponding to the Green-Parity strategy



From the comparison of the four strategies, the following can be noted:

- **Green-Parity** is the strategy that achieves the largest reduction in WACI versus the benchmark, 75% to 76.1 tCO_2e/sales, assuming 28 bp of TE. This WACI reduction comes at the cost of a higher degree of sectoral concentration, as 90% of the portfolio is allocated to just three sectors. Although in absolute terms it is the highest of the four strategies (the MSD is 1.65% and the HI is 9 bp higher than the benchmark portfolio), it is also the most efficient strategy in relative terms, when assessed against the degree of decarbonisation achieved (2.53 vs. 2.03 for the tilting strategy). Regarding asset diversification, this strategy manages to maintain a diversification ratio similar to the benchmark portfolio and above the other alternatives. In addition, this approach improves the Sharpe ratio by 5 bp, which derives from a higher return, with a volatility level similar to the benchmark portfolio, demonstrating that it is potentially feasible to achieve the sustainability goals without assuming a cost in terms of risk-return.

- Second, the **best-in-class** strategy would achieve a 33% reduction in the carbon footprint versus the benchmark to 203.4 tCO_2e/sales, maintaining an identical sectoral composition (MSD=0 and $HI_{port} = HI_{bench}$), assuming a cost in terms of TE of 27 bp and 7 bp in terms of the Sharpe ratio, mainly derived from a lower return on this portfolio. From a relative efficiency perspective, this strategy obtains the lowest decarbonisation ratio versus TE, although it slightly outperforms the exclusion portfolio when compared in terms of sectoral concentration (measured by the HI).

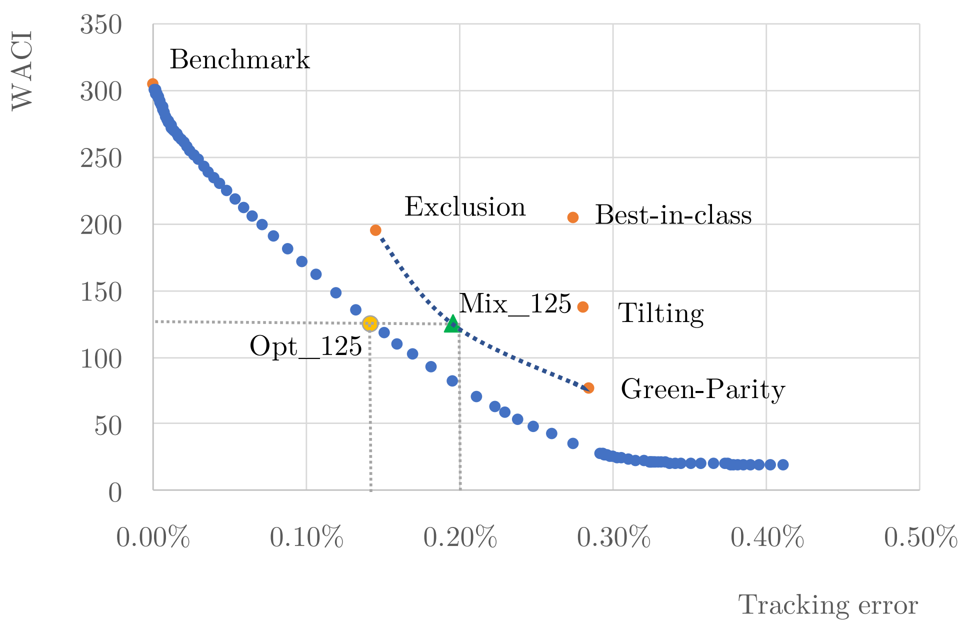
- The **exclusion** strategy reduces the carbon footprint by 36% to 194.7 tCO_2e/sales, with a TE of only 0.15%, the lowest active risk figure of the four strategies. The Sharpe ratio is the same as the benchmark portfolio's and the sectoral composition is very similar (MSD = 0.33% and HI_{port} = 1.6 bp above the benchmark portfolio), while the diversification ratio is slightly lower than the benchmark.

- Finally, the **tilting** strategy decarbonises the portfolio more than the two previous strategies - although less than Green-Parity – by 55% to 136.5 tCO_2e/sales, with a TE of 28 bp, similar to the best-in-class strategy. It obtains a Sharpe ratio that is 4 bp higher than the benchmark, but with a higher cost in terms of sectoral deviation (MSD = 0.82% and HI_{port} = 7 bp above the benchmark portfolio). Regarding relative efficiency, this strategy dominates the exclusion strategy in terms of sectoral diversification but performs worse with respect to TE deviation.

5.2 Combination of SRI strategies

Investors could also combine several strategies to achieve their decarbonisation goal. Suppose that the WACI target for the portfolio is set at 125. It would be feasible to achieve this carbon intensity by using a mixed strategy ('Mix_125'), created from a linear combination of the exclusion strategy (41.2%) and Green-Parity (58.8%), the two most efficient in the WACI-TE space, as presented in Chart 19.

Chart 19. Combination of the exclusion and Green-Parity strategies: 'Mix_125'



There is admittedly a strategy that obtains the same WACI (125) with a lower TE: the 'Opt_125' portfolio on the efficient frontier. Nevertheless, when analysing its performance, some risk-return metrics favour the combined portfolio 'Mix_125'.

Table 6. Results of the ‘Mix_125’, ‘Opt_125’ and benchmark portfolios

	Mix_125	Opt_125	Benchmark
WACI	**125**	**125**	**303.43**
Δ%WACI (vs. benchmark)	-59%	-59%	-
Tracking error	**0.20%**	**0.14%**	**0.00%**
Return	1.96%	1.84%	1.88%
Volatility	2.77%	2.76%	2.77%
Sharpe ratio	0.708	0.667	0.679
VaR	5.84%	5.78%	5.73%
CVaR	16.81%	16.77%	17.07%
MaxDD	6.43%	6.59%	6.59%
Information ratio	0.42	-0.30	-
Diversification ratio (DR)	1.070	1.066	1.073
Mean Squared Deviation (MSD)	0.68%	0.84%	0.00%
Herfindahl index (HI)	24.05%	26.49%	19.65%
Δ%WACI / TE	2.98	4.10	-
Δ%WACI / HI	2.45	2.22	-

As Table 6 shows, both portfolios achieve the same carbon intensity reduction, namely, the target set at 125, although the combined strategy ‘Mix_125’ needs 6 bp more in TE terms. However, other metrics favour this latter portfolio over the one optimized by TE, Opt_125: higher Sharpe and information ratios, better diversification ratio and greater efficiency in terms of WACI - Herfindahl. Thus, the investor would have to balance the price assumed in active risk against the profit achieved in other metrics.

In short, investors must choose the strategy, or mix of strategies, that allows them to simultaneously accomplish their sustainability and financial objectives, striking the desired balance between the two goals. Based on the results obtained for the benchmark portfolio and period analysed, we can conclude that the two objectives are not mutually exclusive, i.e., investors do not necessarily have to forgo a higher risk-adjusted return when setting a decarbonisation objective for a corporate bond portfolio.

6 Conclusion and future lines of work

In recent years, concerns about sustainability and climate change have led investors to incorporate SRI considerations into their investment processes, and to introduce climate risk as an additional factor in portfolio construction and strategic asset allocation.

This paper aims to provide an analytical framework for the incorporation of the carbon footprint into the construction of corporate bond portfolios, trying to isolate the results from purely financial elements by controlling the exposure of assets to different risk factors, such as market risk (interest rate and exchange rate) and credit risk.

The approach underlying the analysis focuses on seeking the optimal asset reallocation within a passive management mandate, where the preferred or structural position is the benchmark (market) portfolio. Within a passive portfolio management context, the investor's fundamental objective is to minimise the active risk assumed against the benchmark portfolio (tracking error), consequently requiring a high degree of indexation in the adopted positions.

Therefore, with the dual objective of fulfilling a passive management mandate and an investment decarbonisation goal, the set of portfolios (efficient frontier) that reduces the initial benchmark WACI while minimising the TE deviation is generated. For the benchmark portfolio and sample period used, we find a trade-off (a negative and convex relationship) between the carbon footprint and TE, implying that further decarbonisation targets involve an increasing cost in terms of deviation in the risk assumed from the benchmark portfolio, not only in terms of TE but also with respect to diversification and sectoral concentration.

Hence it is necessary to quantify, in advance, the level of active risk that needs to be assumed to achieve the desired carbon footprint reduction while fulfilling the passive management mandate. To adequately manage this active risk, investors have a variety of strategies at their disposal that will enable them to meet both their sustainability objectives and their investment mandate at the same time. In addition to the more familiar approaches, such as exclusion*,* best-in-class or tilting, a new strategy called Green-Parity is presented, transferring concepts from risk-based asset allocation to the integration of the carbon footprint into the design of corporate bond portfolios. This proposal is the one that yields the most favourable results among the other strategies used in the study, defining performance ratios (or green return ratios) in which the positive effect of the decarbonisation achieved is compared to the cost assumed in TE or divergence in the sectoral portfolio composition.

Finally, based on the results obtained for the benchmark portfolio and sample period, there is not necessarily a penalty, in terms of risk-return, stemming from the achievement of the decarbonisation objectives. Nevertheless, this conclusion could be affected if variations in the risk factors were allowed and, consequently, the correlation between the assets decreased. In that case, it would be extremely relevant to properly measure and monitor the impact on portfolio financial metrics due to the implementation of the investor's environmental goal.

Some possible future lines of research, without being exhaustive, and following the conclusions reached in this paper, would involve analysing the impact on the results obtained using Scope 3 emissions data for corporate issuers and adapting the decarbonisation exercise for public debt and supranational securities portfolios; the application of the described analytical framework to active portfolio management, where the process of estimating the optimal weights takes into account both the joint temporal dynamics of financial and extra-financial variables, as well as companies' future emission reduction targets; and the possibility of using different metrics, such as ESG scores*,* to replace or complement carbon intensity as a green metric. A final line of work would be the comparison between different strategic asset allocation methodologies: financial ones with objective functions defined in terms of profitability and/or risk (from the Markowitz mean-variance model to other current approaches based on machine learning techniques, such as hierarchical risk parity or hierarchical equal risk contribution) versus methodologies aimed at achieving green objectives, such as those presented in this paper for portfolio decarbonising.

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