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BUILDING NET ZERO PORTFOLIOS OF SOVEREIGN BONDS

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We propose a method for creating a sovereign securities portfolio that gradually reduces its carbon footprint, in line with the Paris Agreement. This allows passive investors to achieve net zero (NZ) targets while maintaining risk-adjusted returns similar to a business-as-usual benchmark. From 2015 to 2021, our approach would have cut carbon intensity by 34.7% with a 7.5% yearly target, compared to just an 8.5% reduction for the benchmark. Total emissions would have dropped by 27.5%, while they would have risen by 25.4% in the benchmark. Notably, NZ portfolios match the benchmark's financial performance and creditworthiness without significant foreign exchange risks.

1 Introduction

Institutional investors urgently seek ways to reduce the carbon intensity of their portfolios. Many investors have already started to report the greenhouse gas (GHG) emissions associated with the underlying holdings of listed equities and corporate bonds in their selected portfolios. However, even though sovereign bonds represent one of the largest asset classes and a significant fraction of diversified investment portfolios, especially among institutional investors, little has been done as regards greening investors' portfolios of sovereign securities.

From an economic perspective, reaching net zero (NZ) emissions means that worldwide, countries should dramatically reduce their GHG emissions through a transformation of the economy, consistent with the Paris Agreement.[1] In this paper, we interpret the NZ logic finance as the continuous and cumulative reduction of the carbon emissions financed by investors through their portfolio. If a sufficient fraction of investors follow NZ finance, asset prices (here, on government bond yields) will be impacted. This new brand of

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market discipline may incentivize countries put in place policies that steer carbon emissions down. Alternatively, if a growing set of countries adopt greener policies and the global economy is moving toward NZ emissions, sovereign in countries that are late to do so may have a harder time placing their debt to investors.

We show how investors can green a portfolio of sovereign securities through the rebalancing of relative country weights in the portfolio based on constituent countries' ability to reduce their carbon intensity, while keeping the portfolio's financial performance close to a benchmark. Investors have both incentives and the capacity to green their portfolios of sovereign securities. On the one hand, countries with a high carbon intensity, regardless of their level of debt outstanding, face greater risks related to the transition to a low-carbon economy. On the other hand, investors' portfolio adjustment may provide financial incentives for sovereign issuers to reduce carbon emissions in their jurisdiction.

To construct an NZ portfolio and analyse how the NZ strategy accelerates portfolio-level decarbonisation, we start by choosing a business-as-usual (BAU) benchmark of sovereign bonds, for instance the family of J.P. Morgan's Government Bond Indices, covering the largest sovereign issuers from both advanced and emerging economies. We then collect GHG emission data and construct carbon intensity metrics for each country constituent of these indices. Finally, we consider the construction of an institutional investor's portfolio over a given period of time along two dimensions: to reduce the portfolio's carbon intensity, measured as per capita CO_2 emissions from domestic consumption, and to keep the returns as close as possible to those of the BAU benchmark.

Using backward-looking emission data between COP 21 (end 2015) and COP 26 (end 2021), the NZ portfolio that we propose achieves a carbon intensity reduction of 34.7% with an annual decarbonisation rate of 7.5% by adjusting country weights.[2] In our baseline strategy, a country's carbon intensity is computed by scaling the carbon emissions from the country's final consumption, including both domestically produced goods and services and the imports, by the total population (consumption-based approach). In comparison, the BAU benchmark portfolio, where country weights reflect the relative market value of countries' sovereign debts, implies a much more limited reduction in carbon intensity, by 8.5%, over the same 6-year window. This 8.5% reduction reflects countries' actual decarbonisation efforts between 2015 and 2021 weighted by the market capitalisation of their respective debts in the BAU benchmark. In terms of overall emissions, the gain is even more substantial, as the emissions of the NZ portfolio could be reduced by as much as 27.5% (with the same 10% target), while the emissions of the BAU benchmark would have increased by 25.4%.

In addition, the NZ portfolio retains the same credit rating (AA-) as the BAU benchmark and tracks closely the benchmark's financial performance. The annual returns and ex post Sharp ratio of the NZ portfolio are only slightly below those of the BAU benchmark and return volatilities do not even increase. To achieve this ambitious objective of carbon intensity reduction, the rebalancing of country weights in the NZ portfolio is radical if no additional constraints are imposed to limit the range of weight changes. For instance, among advanced economies, it requires reducing the weight of the United States from 37.7% to 19.5% (with a 7.5% annual decarbonisation target) and consequently increasing those of European countries having made strong decarbonisation efforts and strong credit ratings. Over time, there is also an overall weight shift from advanced economies toward emerging market economies given lower consumption-based carbon intensity there. The overall weight of emerging market economies would increase from 8.9% in the BAU benchmark to 17.3% in the NZ portfolio with a 7.5% target. Several emerging economies benefit from increased investment, including China and India. However, the main beneficiaries are Latin American countries, such as Chile, Mexico, and Uruguay. In relative terms, these countries have low consumption-based GHG emissions per capita.

These changes in country weights in the NZ sovereign portfolio may be perceived as excessive by institutional investors. We thus lay out an alternative reallocation approach with additional restrictions in the composition of the portfolio. First, we impose upper and lower limits to the changes in country weights in each period. At any point in time, a country's share in the portfolio cannot fall below 50% or exceed 150% relative to its weight in the BAU benchmark. This restriction takes into account the fact that some countries may be unable or unwilling to increase their issuance of public debt even if investors would be willing to increase their holding of sovereigns in low carbon jurisdictions. Abrupt reallocations could also destabilise sovereign debt markets. For example, given the dominance of the U.S. dollar, investors are unlikely to diversify away from U.S. Treasury bonds. Second, we set a limit on the changes in the overall creditworthiness of the portfolio, as investors would prefer to preserve credit and currency risks exposures similar to the one of the BAU benchmark. This more constrained approach, which limits changes in country weights, also attenuates the reduction in carbon intensity. Our simulations show that a 7.5% annual reduction in the portfolio's carbon intensity will only lead to a cumulative 20.6% reduction over 6 years, instead of 34.7% in the unconstrained case.

Our simulation results are sensitive to the measurement of the portfolio's carbon intensity. For the baseline analysis, we stick to the per-capita carbon intensity of a country's final demand. We will also demonstrate how such a decarbonisation can be achieved when we adopt a production-based metric of the carbon intensity.

Our work is closely related and contributes to three strands of literature, namely the effort to measure sovereign carbon intensity, the relationship between climate risks and portfolio management and returns, and finally the impact of climate risks on sovereign debt. First, the debate on the carbon footprint of sovereign securities is much less mature than the one on carbon disclosure and carbon intensity measures of equities and corporate bonds (Ehlers *et al.*, 2020). Many technical issues prevent clarity on methodologies to evaluate the carbon footprint of sovereigns. Domínguez-Jiménez and Lehmann (2021) discuss the definition of the relevant scope of emissions for sovereign bond issuers, namely whether to include emissions from the public sector only or to take into account the economy-wide emissions. Related, when looking into economy-wide emissions, emissions may refer to domestic production (from domestic emissions, including emissions embodied in exported goods and services) or local consumption (domestic emissions and those embodied in trade, netting out exports). PCAF (2022) launched the second version of the Global GHG Accounting and Reporting Standard for the Financial Industry in December 2022, and sovereign debt methodology and guidance on emissions removals. This accounting initiative also supports the use of a more holistic approach to report country's carbon emissions, especially to incorporate scope 3 emissions from imports. Following Burns *et al.* (2016), Desme and Smart (2018), and PCAF (2022), we adopt in our baseline analysis a consumption-based carbon emissions metric, scaled by population. This metric includes not only carbon emissions that are generated from domestic production, but also those from imported goods and services. We argue that this metric captures carbon leakages, especially in advanced economies, as people there tend to consume more imported goods and services. We also investigate a territorial approach to carbon intensity, i.e., a production-based carbon emission metric, encompassing emissions from domestic production used for both final consumption in the territory and exports. The financial industry is also paying increasing attention to how to decarbonize sovereign securities portfolios. Kaula *et al.* (2022) propose a way to construct a Paris-aligned sovereign securities portfolio by overweighting the countries best prepared for the transition and those countries with lower carbon emissions. The Assessing Sovereign Climate-related Opportunities and Risks (ASCOR) Project establishes tools to assess the sovereign exposure to climate risk and the plans established by governments to transition to a low-carbon economy but does not design any related NZ investment strategies.[3]

Second, our work is related to the literature on climate risks and portfolio management. The current literature focuses mostly on greening portfolios of corporate securities, primarily because the prevailing carbon disclosure requirements concern listed equities and to a lesser extent corporate bonds. Andersson *et al.* (2016) develop an investment strategy that allows long-term passive investors to hedge climate risks without sacrificing financial returns. Bolton and Kacperczyk (2021) show that investors demand compensation for their exposure to carbon emissions risks and exclude high-carbon emitters from investment in a few salient industries. Jondeau *et al.* (2021) examine strategies for an investor to trim the carbon footprint of a portfolio of listed equities. Using the MSCI global stock portfolio of 2010 as a benchmark, some of us show that a passive investor could have cut the portfolio's carbon footprint by 64%, namely a 10% reduction per year over 10 years, by excluding the most polluting corporates and this is without collateral damage to the portfolio's financial returns. Fahlenbrach and Jondeau (2023) propose strategies to green the Swiss National Bank (SNB)'s portfolio. They find that the carbon footprint from the SNB's U.S. equity portfolio would be reduced by 27% in 2020, with no impact on the portfolio's financial performance, should the SNB exclude the top 1% polluting firms and reinvest in the companies with the lowest intensity in the same sector. Bressan *et al.* (2022) also show that the impact on individual bonds' yields from climate-risk driven portfolio rebalancing is rather limited.

Finally, our research also contributes to the literature on the impact of climate risks on sovereign debt, especially on sovereign bond yields. The existing literature often uses indicators of climate change vulnerability and resilience to measure the impact of physical risks on the cost of government borrowing (Beirne *et al.*, 2021; Cevik and Jalles, 2022; Zenios, 2022). For instance, Beirne *et al.* (2021) find that the effects of transition risks on sovereign bond yields are on average lower than for physical risks across a sample of 40 advanced and emerging market economies. A more recent study by Bingler (2022) finds that climate transition risks are increasingly priced-in for longer-term government bonds of higher-rated countries. Our empirical analysis points to potentially large transition risks for sovereign bond issuers should investors collectively rebalance their portfolios towards countries with lower carbon footprints.

The rest of the paper is organised as follows. Section 2 presents the data that we use to construct the NZ portfolio from a BAU benchmark. Section 3 describes the portfolio optimisation methodology. Section 4 presents both the baseline unrestricted results and the results from optimisation with additional constraints. Section 5 discusses policy implications of our work and concludes.

2 Data

2.1 Sovereign bond index

We first choose a BAU benchmark before embarking on the journey of reducing its carbon footprint. For this purpose, we use J.P. Morgan's Government Bond Indices, as these are widely used by investors and they provide us with financial data at both the aggregate and country levels, including individual country weights. On the one hand, the Government Bond Index Global (GBI Global), launched in 1989, includes government bonds from 13 advanced economies. It incorporates only liquid, fixed-rate debt in local currencies with no callable, putable, or convertible features. On the other hand, the Government Bond Index – Emerging Market Broad (GBI EM Broad), launched in 2005, is a comprehensive benchmark for emerging market, currently covering 21 emerging market economies. This index includes regularly traded, fixed-rate, domestic-currency government bonds accessible to international investors.[4]

The first set of important data series from J.P. Morgan indices are country weights, which are calculated based on the market capitalisation of their outstanding government bonds. Table 1 presents the country weights within the BAU benchmark at the end of 2015 and 2021, namely the start and end years for our portfolio rebalancing exercise. Total weights in Table 1 (the second and the sixth columns) refer to the shares of countries—advanced and emerging economies altogether—in the indices. Regional weights (the third and the seventh columns) indicate a country's share within one of the two country groupings—advanced economies or emerging economies. Among advanced economies, the United States and Japan exhibit the largest regional weights, close to 46.3% and 18.6% in 2021, respectively. Next are the United Kingdom and France, with weights around 7%. Among emerging economies, countries with the largest regional weights are China (46.8%) and India (16%). Indonesia and Brazil, with their respective weights of 5.7% and 4.5% of the index, are distant followers.

Second, we extract return data for all the constituents of the J.P. Morgan indices. All returns used in our analysis are total returns, which include changes in both clean price and accrued interest, converted into U.S. dollars. All coupons received are immediately reinvested into the national market. In addition, J.P. Morgan indices report both returns hedged or unhedged against currency risks. The hedged index is obtained by adjusting the unhedged index with a one-month currency forward contract. As it is well known, currency returns are more volatile than sovereign debt returns. Therefore, hedging or not hedging largely affects the portfolios' financial performance. In particular, the NZ portfolios could entail large swings when securities are denominated in different currencies. In our subsequent analysis, we report the financial performance for both hedged and unhedged portfolios.

2.2 GHG emissions

As we consider the decarbonisation of a portfolio of sovereign bonds, several questions arise concerning the use of the GHG emissions data. (1) What is the perimeter of emissions to be considered, e.g., government or country-wide emissions? (2) Should emissions be based on domestic production or on domestic consumption? (3) If we consider carbon intensity, how should we normalise emissions when production-based or consumption-based metrics are used? We briefly discuss these questions in this subsection.

Table 1 Country weight and carbon intensity.

Country	End of 2015				End of 2021			
	Benchmark		GHG emissions		Benchmark		GHG emissions	
	Total weight	Regional weight	Consump. per capita	Prod. per GDP	Total weight	Regional weight	Consump. per capita	Prod. per GDP
Panel A: Advanced economies								
Australia	1.20	1.29	21.93	396.1	1.55	1.73	18.74	354.0
Belgium	1.69	1.81	24.65	257.4	1.37	1.53	25.33	225.8
Canada	1.16	1.25	21.61	466.4	1.77	1.99	19.30	416.1
Denmark	0.42	0.45	12.02	165.9	0.29	0.32	12.40	124.7
France	6.38	6.83	10.17	191.5	5.91	6.62	9.33	160.7
Germany	4.96	5.31	14.50	269.8	4.03	4.50	13.35	203.4
Italy	6.45	6.90	9.45	240.7	5.31	5.94	9.30	207.7
Japan	19.63	21.02	11.74	297.0	16.60	18.57	10.26	250.2
Netherlands	1.68	1.80	20.19	252.1	1.16	1.30	21.57	199.2
Spain	3.60	3.86	8.70	282.6	3.43	3.84	7.70	217.3
Sweden	0.33	0.35	10.91	107.5	0.18	0.20	10.05	85.6
United Kingdom	7.37	7.90	11.92	173.8	6.39	7.15	9.24	132.2
United States	38.49	41.23	23.89	371.3	41.39	46.31	22.50	312.1
Sum / average	93.36	100.0	16.03	285.1	89.37	100.0	14.74	234.1
Panel B: Emerging economies								
Argentina	—	—	6.36	585.1	0.00	0.01	5.16	597.0
Brazil	0.68	10.21	5.11	627.0	0.48	4.50	4.13	601.6
Chile	0.04	0.67	6.51	441.2	0.08	0.73	6.16	432.7
China	1.98	29.77	8.16	1148.1	4.97	46.80	8.97	848.3
Colombia	0.17	2.51	3.06	524.7	0.16	1.50	2.82	558.9
Czech Rep.	—	—	13.80	680.7	0.18	1.70	14.71	519.0
Dominican Rep.	—	—	3.27	427.2	0.01	0.06	3.06	345.3
Hungary	0.15	2.20	9.16	492.9	0.13	1.27	10.41	412.7
India	0.95	14.26	2.27	1388.1	1.70	16.00	2.31	1127.6
Indonesia	0.26	3.95	3.03	975.8	0.61	5.69	3.04	849.0
Malaysia	0.27	4.06	11.07	1078.5	0.33	3.12	10.05	940.0
Mexico	0.70	10.60	6.52	590.5	0.42	3.92	5.57	530.2
Peru	0.05	0.72	2.88	494.2	0.08	0.76	2.52	451.0
Philippines	0.01	0.20	1.92	682.0	0.01	0.05	1.81	602.1
Poland	0.33	4.94	9.59	817.4	0.28	2.63	10.13	614.9
Romania	0.08	1.20	6.38	640.9	0.12	1.09	7.28	463.9
Russia	0.15	2.24	8.05	1532.8	0.29	2.73	7.61	1448.4
South Africa	0.30	4.59	7.77	1603.6	0.38	3.56	6.16	1531.3
Thailand	0.24	3.56	6.07	1049.1	0.35	3.28	5.07	865.9
Turkey	0.29	4.34	7.80	556.5	0.05	0.44	7.42	493.7
Uruguay	—	—	8.70	657.0	0.00	0.05	7.73	669.1
Sum / average	6.64	100.0	6.56	1006.0	10.62	100.0	6.98	886.9

Note: This table reports the number of firms in the Trucost dataset; the number of firms in the J.P. Morgan index and its two main components (advanced and emerging economies); the proportion of firms in the J.P. Morgan index with carbon measures in Trucost; and the proportion of the market capitalisation of the J.P. Morgan index with carbon measures in Trucost. The last line of each panel reports the sum of country weights and the weighted average intensity, based on J.P. Morgan index weights.

GHG emissions attributed to sovereign bonds can be defined according to two distinct approaches. On the one hand, one may consider solely the emissions stemming from the public sector's consumption of goods and services. On the other hand, one may argue that government decisions are likely to affect the entire economy, warranting the inclusion of all emissions originating within the country. Despite potential double counting with private sector emissions, we follow the latter approach because it encourages governmental efforts to curtail overall country's emissions through all policy and financing tools at its disposal. The perimeter of our analysis is also in line with the recommendations articulated by PCAF (2022).

The second key question is whether GHG emissions should be measured according to a production-based accounting or a consumption-based accounting. For practical reasons, governments typically adopt a territorial emissions approach, focusing on GHG emissions within a given territory, regardless of the ultimate destination of the goods and services produced (production-based accounting). Recommended by the Kyoto Protocol, this territorial emissions approach is adopted by the UNFCCC for the annual national inventories and is typically referenced by sovereigns in their Nationally Determined Contributions (NDCs). However, this territorial accounting does not incorporate countries' scope 3 emissions, namely those attributable to non-energy imports from abroad (PCAF, 2022). Consequently, the production-based accounting may result in carbon leakages, as advanced economies may relocate the most polluting production to countries with less stringent environmental regulations while continuing to consume the output through imports. An alternative approach consists in measuring GHG emissions resulting from domestic final demand, i.e., all goods and services consumed in a given country, encompassing both emissions from domestic production and imports (consumption-based accounting). With this approach, emissions embedded in imports are added to those generated from domestic consumption, while emissions from exports are excluded. Although the adoption of this consumption-based metric is not yet widespread, PCAF (2022) deems it a more holistic approach and recommends financial institutions to employ it. In our empirical analysis, we primarily adopt the consumption-based approach, although we also present results based on the production-based approach, as they offer complementary perspectives on a country's emissions and yield significant divergences in terms of allocation.[5]

Third, the normalisation of GHG emissions is imperative for cross-country comparability. One method for achieving this is through an ownership approach, where we quantify "financed emissions" by weighting a country's emissions by the fraction of government debt financed by the investor. However, this approach would not be consistent given our choice to consider a country's overall emissions rather than solely those of the public sector. Moreover, in the context of a sovereign bond portfolio, it also raises the issue of the large heterogeneity in size of public debt across countries.[6] An alternative normalisation approach involves the carbon intensity of the bond portfolio. In our perspective, the choice of the denominator should align with the chosen accounting approach. We standardise the production-based emissions of a country i, denoted by $E_{i,t}^{(prod)}$, by its domestic GDP, as GDP measures the value of goods and services produced within the country. Consequently, our measure of carbon intensity in the production-based approach is expressed as:

$$CI_{i,t}^{(prod)} = \frac{E_{i,t}^{(prod)}}{GDP_{i,t}}. \quad (1)$$

In our data, GDP is expressed in constant 2010 U.S. dollars. The carbon intensity from this approach is expressed in tons of CO_2 equivalent per million U.S. dollars of GDP.

The consumption-based GHG emissions, denoted by $E_{i,t}^{(cons)}$, are adjusted by the country's population to reflect the carbon consumption at the individual level. The carbon intensity from this approach is defined as:

$$CI_{i,t}^{(cons)} = \frac{E_{i,t}^{(cons)}}{Pop_{i,t}} \tag{2}$$

and expressed in tons of CO_2 equivalent per capita.

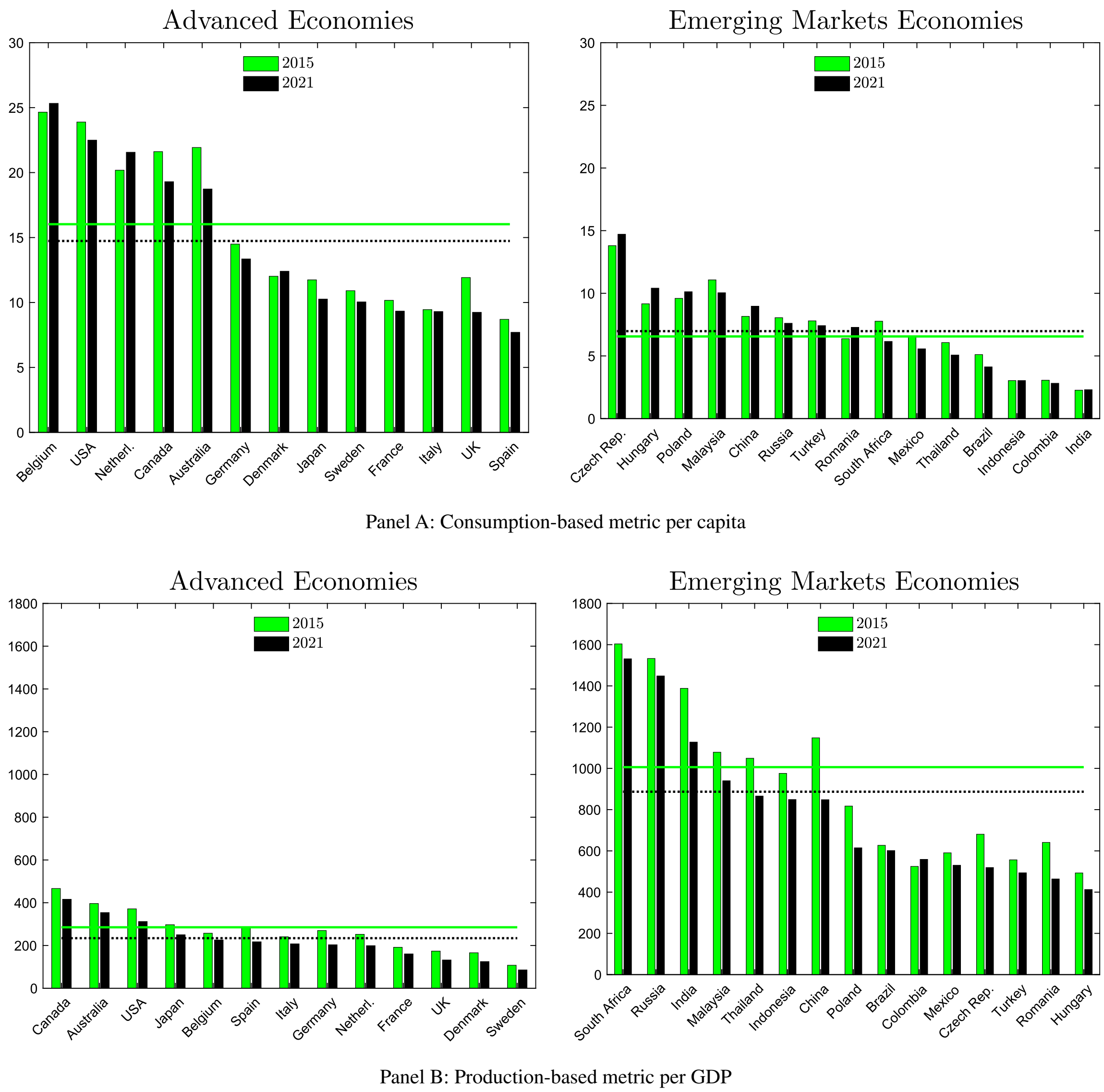


Figure 1 Carbon intensity by country.

This figure displays the carbon intensity of the various countries under consideration for 2015 (in green) and 2021 (in black). Carbon intensity is the consumption-based metric in tons of CO_2 equivalent per capita in Panel A and the production-based metric in tons of CO_2 equivalent per million U.S. dollars of GDP in Panel B. Countries are sorted by decreasing carbon intensity as of 2021. Blue and red horizontal lines correspond to the weighted-average numbers in 2015 and 2021.

Data pertaining to countries' GHG emissions come from the Trucost sovereign environmental database. The primary data source is PRIMAP, which offers a comprehensive collection of emission pathways for each country and Kyoto Protocol gas, spanning the years 1850 to 2021 (Gütschow *et al.*, 2016, 2023). The additional economic variables that are used to scale GHG emissions data for cross-country comparison are collected from the World Bank World Development Indicators.

Both measures of carbon intensity are reported in Table 1 at the end of 2015 and 2021. As expected, when considering consumption-based carbon intensity, the carbon intensity metrics for emerging economies are lower than those for advanced economies. In 2021, the average carbon intensity, weighted by the market weights of the J.P. Morgan index, is equal to 14.7 tons per capita for advanced economies and 7 tons for emerging economies, as illustrated in Figure 1 (Panel A, black dashed lines). Primary contributors in 2021 include Belgium, the United States, and the Netherlands (above 20 tons) among advanced economies and the Czech Republic, Hungary, Poland, and Malaysia (above 10 tons) among emerging economies.

In contrast, advanced economies exhibit lower production-based carbon intensity metrics compared to their emerging economy counterparts, attributed to more efficient production processes and the outsourcing of some of the most polluting industries abroad (Figure 1, Panel B). In 2021, advanced economies recorded an average of 234.1 tons per million U.S. dollars of GDP based on the production-based carbon intensity metric, while emerging economies, on average, generated 886.9 tons per GDP (all figures weighted by the market weights of the J.P. Morgan index). Notably, Canada, Australia, and the United States are the primary contributors among advanced economies, while South Africa, Russia, and India are the main contributors among emerging economies.

We also observe that all advanced economies have reduced their carbon intensity for both consumption-based and production-based metrics between 2015 and 2021, with Denmark being the exception, experiencing a slight increase in consumption-based carbon intensity in 2021. All emerging economies have reduced their production-based intensity except Colombia but several of them have increased their consumption-based intensity, given their economic development which allows people to upgrade their consumption from foreign imports.

3 Constructing an NZ Portfolio

At the end of month t, we consider a set of N_t sovereign bonds are available in the BAU benchmark. Their weights are denoted by $\alpha_{1,t}^{(b)} = \{\alpha_{1,t}^{(b)}, \ldots, \alpha_{N_t,t}^{(b)}\}$. The vector of simple returns of these securities in month $t+1$ is denoted by $R_{t+1} = \{R_{1,t+1}, \ldots, R_{N_t,t+1}\}$. The performance of the BAU benchmark at the end of $t+1$ is simply $R_{t+1}^{(b)} = \sum_{i=1}^{N_t} \alpha_{i,t}^{(b)} R_{i,t+1}$.

Given that the carbon intensity data for country i is available solely on an annual basis, with $CI_{i,t}$ denoting the (production-based or consumption-based) intensity of the year associated with month t, we assume, for simplicity, that $CI_{i,t}$ is readily available at the end of the year.[7] As carbon data is available on an annual basis only, we consider an NZ portfolio whose weights are determined at the end of each year, although the dynamics of weights and returns are measured at a monthly frequency.

We proceed by describing how the weights of the NZ portfolio are determined at the end of a given year. Then, we describe how performance metrics are computed ex post on a monthly basis.

The investor determines the portfolio weights $\alpha_t^{(p)} = \{\alpha_{1,t}^{(p)}, \ldots, \alpha_{N_t,t}^{(p)}\}$ to meet the emission reduction target, striving to maintain the financial characteristics of the portfolio as close as possible to those of the BAU benchmark. If we assume that month t corresponds to December of year Y, the target is set as $CI_t^{(target)} = CI_{t_0}^{(b)}(1-\theta)^{(Y-Y_0)}$, where $CI_{t_0}^{(b)} = \sum_{i=1}^{N_{t_0}} \alpha_{i,t_0}^{(b)} CI_{i,t_0}$, Y_0 is the starting year and t_0 is corresponds to December of year Y_0, and θ is the rate of carbon intensity reduction. Each year t, we impose the restriction that $CI_t^{(p)} = \sum_{i=1}^{N_t} \alpha_{i,t}^{(p)} CI_{i,t} \leq CI_t^{(target)}$. The portfolio return is denoted by $R_{t+1}^{(p)} = \sum_{i=1}^{N_t} \alpha_{i,t}^{(p)} R_{i,t+1}$.

We examine two metrics for assessing proximity to the BAU benchmark. The first metric is the tracking error volatility, which represents the volatility of the difference between the performance of the NZ portfolio and that of the BAU benchmark. The ex-ante tracking error is defined as:

$$TE_t^{(p)} = \sqrt{(\alpha_t^{(p)} - \alpha_t^{(b)})' \Sigma_t (\alpha_t^{(p)} - \alpha_t^{(b)})}, \quad (3)$$

where $\Sigma_t = V_t(R_{t+1})$ is the sample covariance matrix of returns computed using the last 60 monthly returns.[8]

The second metric is the active share. As defined by Cremers and Petajisto (2009) and Petajisto (2013), the ex-ante active share measures the difference between the weights in the NZ portfolio and in the BAU benchmark, namely:

$$AS_t^{(p)} = \frac{1}{2} \sum_{i=1}^{N_t} |\alpha_{i,t}^{(p)} - \alpha_{i,t}^{(b)}|. \quad (4)$$

To evaluate the cost of rebalancing the portfolio, we also report the turnover, which measures the change in the portfolio positions. Given that the weights of different securities may fluctuate between two rebalancing dates owing to shifts in market prices, we measure turnover as follows:

$$TO_t^{(p)} = \frac{1}{2} \sum_{i=1}^{N_t} |\alpha_{i,t}^{(p)} - \alpha_{i,t^-}^{(p)}|, \quad (5)$$

where $\alpha_{i,t^-}^{(p)} = \alpha_{i,t-1}^{(p)}(1+R_{i,t})/(1+R_t^{(p)})$ measures the weight of country i just before the rebalancing at date t.

We also posit that the investor requires the NZ portfolio to have the same credit rating as the BAU benchmark. This assumption aligns with the prevalent strategy adopted by the majority of institutional investors. The rationale behind this assumption serves a dual purpose: first, to ensure coherence in the investor's credit rating, and second, to forestall substantial reallocations across country segments. Specifically, this helps mitigate pronounced shifts from advanced to emerging economies in scenarios utilising consumption-based intensity and vice versa when employing production-based measures.

To summarise our strategy of portfolio rebalancing, we first set out a target $CI_t^{(target)}$ for the reduction in carbon intensity. This reduction is gauged using two distinct carbon

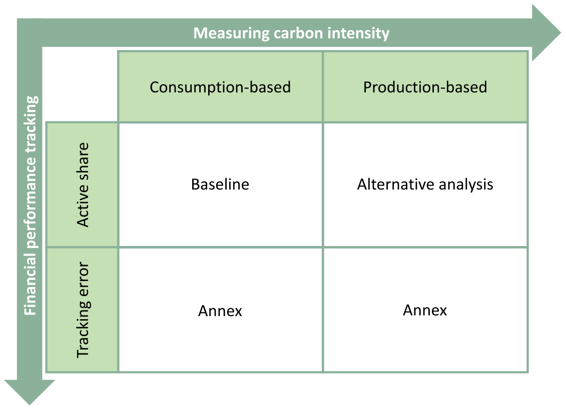
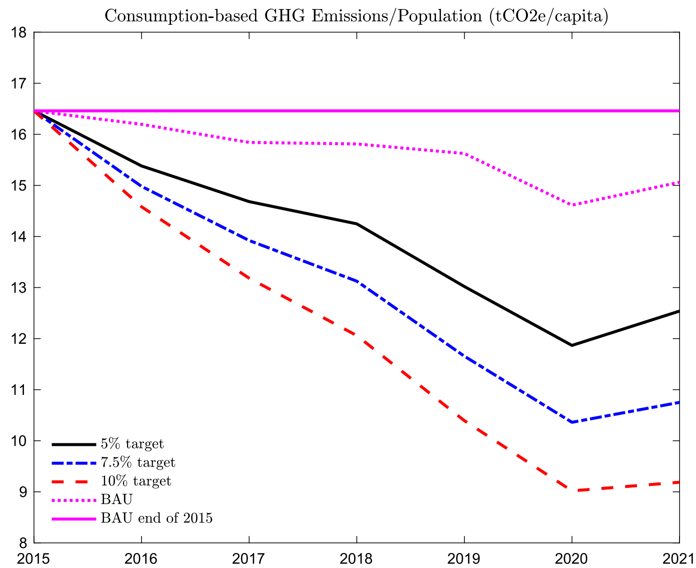
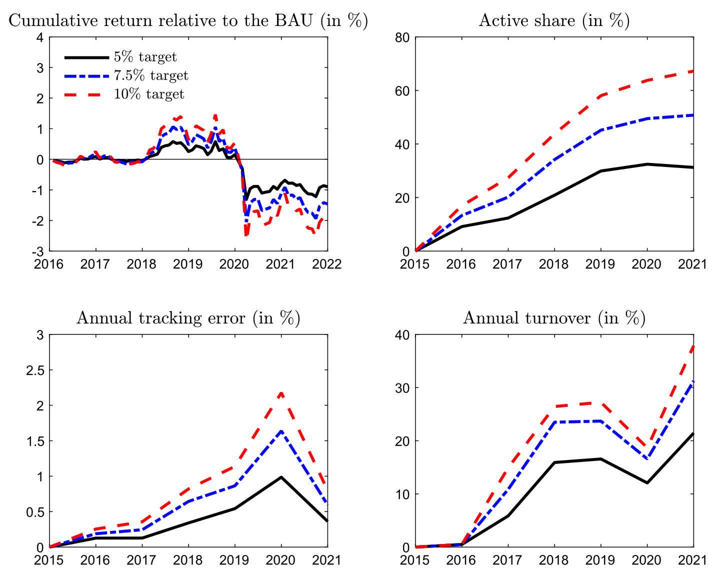


Figure 2 Scenarios based on carbon intensity metrics and performance tracking method.



Panel A: Consumption-based carbon emissions per capita



Panel B: Financial Performance

Figure 3 Minimisation of the tracking error: Portfolio performance (Consumption per capita metric).

Panel A of this figure displays the consumption-based carbon emissions per capita of the various portfolios: the NZ portfolios with 5% (in black), 7.5% (in blue), and 10% (in red) reduction target and the BAU benchmark (in magenta). Panel B reports financial performance measures: the cumulative return relative to the BAU benchmark (monthly returns from 2016 to 2021), the active share, the annual tracking error, and the annual turnover.

intensity metrics: consumption-based GHG emissions per capita (used for the baseline analysis) and production-based GHG emissions per million U.S. dollars of GDP. We prefer the consumption-based approach because it gives stronger incentives for advanced economies to contribute more substantially to the carbon emission reduction. This choice aligns with the ambitious NZ strategy articulated by European Union countries, incorporating quantifiable targets for 2020, 2030, and 2050.[9] The second dimension of our methodology is to use a portfolio optimisation tool to track the financial performance of the BAU benchmark. The two strategies, namely minimising the tracking error and the active share, are detailed above and are complementary with each other. Petajisto (2013) in fact argues that tracking error and active share focus on different aspects of active management. The tracking error is a proxy for systematic factor risk, whereas the active share emphasises asset selection. In the baseline analysis, we focus on the tracking error and present the results using active share method in the Online Appendix. The diagram in Figure 2 provides an overview of the two dimensions shaping our NZ investment strategy and the various scenarios we will examine in the rest of the paper.

Finally, we shortly describe the ex-post financial performance metrics employed to compare the NZ and BAU portfolios. While the allocation is determined annually, tracking error and active share are computed over the entire sample using monthly data. Ex post, given the absence of intra-year rebalancing in the NZ portfolio, its weights fluctuate based on the dynamics of sovereign bond returns (the same applies to the BAU benchmark). So, if we consider a rebalancing at the end of the year (in month t), the subsequent 12-month weights will vary as follows: $\alpha_{i,t+\tau}^{(p)} = \alpha_{i,t}^{(p)} \prod_{h=1}^{\tau} \left(\frac{1+R_{i,t+h}}{1+R_{t+h}^{(p)}}\right)$, for $\tau = 1, \ldots, 12$, until the next rebalancing at the end of the next year (in month $t+12$).

Using these weights, we compute the ex-post tracking error as the variance of the difference between the monthly returns of the NZ portfolio and the BAU benchmark over the sample: $TE^{(p)} = \sqrt{\frac{1}{T}\sum_{t=1}^{T}(R_{t+1}^{(p)} - R_{t+1}^{(b)})^2}$. The ex-post active share over the sample of T months is computed as follows: $AS^{(p)} = \frac{1}{T} \times \sum_{t=1}^{T} \frac{1}{2} \sum_{i=1}^{N_t} |\alpha_{i,t}^{(p)} - \alpha_{i,t}^{(b)}|$.

4 Empirical Results

4.1 NZ portfolio under the unrestricted perspective

We simulate our NZ investment strategy with annual decarbonisation targets θ of 5%, 7.5%, and 10%, respectively, for a period of 6 years, using historical data. These decarbonisation targets are chosen based on the literature and the projected GHG emissions levels to remain within the global carbon budget to reach carbon neutrality in 2050. The longer investors delay the adoption of NZ alignment, the higher the annual decarbonisation target will be required. Given the delays that have already occurred in the NZ transition, we use a 7.5% decarbonisation target as our baseline scenario. This number is also in line with our calculation using the projected GHG emissions by 2030 in the UNFCCC report for COP27. Global carbon emissions need to be further reduced by 48.5% between 2022 and 2030 to achieve the NZ transition in 2050, namely an annual reduction by approximately 8% is required.[10]

The investor minimises the tracking error to satisfy the carbon intensity reduction target using the consumption-based carbon intensity metric. The allocation is performed over a 6-year window, commencing with the end-2015 carbon emission data as the starting point for a first optimisation exercise in 2016. The exercise ends in 2021, as most countries' emission data for 2022 will only be available by the end of 2023.

Results of the optimisation strategy are presented in Figure 3. In Panel A, the trajectory of the carbon intensity is illustrated for both the BAU benchmark (magenta dashed line) and the NZ portfolio with three distinct annual decarbonisation targets (5% in black, 7.5% in blue, and 10% in red).

The horizontal magenta line indicates the carbon intensity of the BAU benchmark at the end of 2015, i.e., the starting point for the decarbonisation process. At first glance, the NZ portfolio can achieve a more pronounced decarbonisation compared to the BAU benchmark. Notably, the year 2020 witnessed a trough in the portfolio's carbon intensity, attributed to disruptions in international trade caused by extensive lockdowns amid the Covid-19 pandemic, leading to reduced consumption of imported goods.

Table 2 provides a detailed overview of the summary statistics concerning the carbon and financial performance of the NZ portfolio in comparison to the BAU benchmark. First, the carbon intensity of the BAU benchmark remains stable throughout most years in the sample period. Ultimately, the aggregate intensity experienced an overall decrease of 8.5% over the 6-year period, with a reduction by 8.9% in 2020 attributed to the impact of the Covid-19 crisis. In 2021, the carbon intensity of the BAU benchmark registered an increase coinciding with the easing of pandemic-related lockdowns in most countries. In absolute terms, total emissions even exhibit a growth of 25.4% throughout the sample.[11]

Second, we observe that portfolios targeting annual carbon reductions of 5%, 7.5%, and 10% achieve a nearly linear decline in carbon intensity over the 6-year period. The cumulative decarbonisation goes to 44.2% with the annual reduction target of 10%. This result is accomplished by overweighting economies with low carbon intensity and underweighting (and sometimes excluding) economies with high carbon intensity. These portfolios exhibit an ex post annual carbon intensity reduction of 4.5%, 6.9%, and 9.3%, respectively. The ex post reduction is slightly below the targeted reduction because certain economies, despite having low carbon intensity, experienced an increase in carbon intensity throughout the sample period.

Third, the targeted intensity objectives lead to a more pronounced reduction in overall emissions, amounting to a modest increase by 0.4% and decreases by 27.5% and 52% for the 5%, 7.5% and 10% targets, respectively. This substantial reduction relative to the BAU benchmark is attributed to the massive decrease in the relative weight of certain countries, notably the United States, resulting in a considerable lowering of emissions levels.

Regarding financial performance, Figure 3 Panel B reports the cumulative returns of the NZ portfolio in relation to the BAU benchmark, the active share ($AS^{(p)}$), the annualised tracking error volatility ($TE^{(p)}$), and the annualised turnover ($TO^{(p)}$), respectively.[12] Table 2 offers further details. On average over the period, the (hedged) annual return of the BAU benchmark is equal to 3.3% with a Sharpe ratio of 1. The financial performance of the NZ portfolios closely aligns with that of the BAU benchmark. With the 7.5% target, the NZ portfolio slightly underperforms the BAU benchmark with an average annual return of 3.2% and a Sharpe ratio close to 1. Additionally, the NZ strategy comes at the cost of a moderate annualised tracking error, which is equal to 0.8%. Moreover, the active share and the annual turnover are equal to 35.5% and 21.2%, respectively. Overall, these financial metrics suggest that the cost of decarbonisation is moderate and is mainly reflected in the increasing distance to the BAU benchmark.

Table 2 also reports the financial performance of the portfolios without hedging. This investment strategy would experience lower returns and higher volatility compared to the benchmark, resulting in an overall performance significantly inferior to that of the hedged portfolio. The diminished performance is due to the NZ portfolio

Table 2 Minimisation of the tracking error: Portfolio performance (Consumption per capita metric).

	BAU benchmark	NZ portfolio		
		5% reduction	7.5% reduction	10% reduction
Panel A: General performance				
Annual active share	—	22.7%	35.5%	46.2%
Annual turnover	0.0%	14.4%	21.2%	25.0%
Sum AE weights	91.1%	86.5%	82.7%	79.4%
Average rating	AA-	AA-	AA-	AA-
Change in GHG intensity	−8.5%	−23.8%	−34.7%	−44.2%
Change in GHG emissions	25.4%	0.4%	−27.5%	−52.0%
Panel B: Performance of hedged portfolio				
Annual return	3.28%	3.15%	3.08%	3.01%
Annual volatility	3.23%	3.16%	3.17%	3.20%
Ex post Sharpe ratio	1.02	1.00	0.97	0.94
Annual tracking error	—	0.50%	0.83%	1.10%
Panel C: Performance of unhedged portfolio				
Annual return	2.99%	2.94%	2.89%	2.83%
Annual volatility	5.04%	5.34%	5.80%	6.32%
Ex post Sharpe ratio	0.59	0.55	0.50	0.45
Annual tracking error	—	1.15%	2.10%	2.93%

Note: Panel A of this table reports some characteristics of the BAU benchmark and the NZ portfolios with 5%, 7.5%, and 10% reduction targets: the average annual share, the annual turnover, the sum of weights in advanced economies, the average rating, and the change in carbon intensity and emissions. Panels B and C report financial performance of the hedged and unhedged portfolios, the annual return and volatility, the ex-post Sharpe ratio, and the annual tracking error. The period is 2016–2021.

rebalancing assigning higher weights to European countries that issue sovereign securities in euro while the portfolio returns are denominated in U.S. dollars. Throughout the rebalancing period, the U.S. dollar appreciated against the euro, thereby diminishing returns from euro-denominated assets. The Sharpe ratio of the 7.5% target strategy is equal to 0.97 and 0.5 for the hedged and unhedged portfolios, respectively. In addition, the tracking error is several times higher for the unhedged strategy (2.1% against 0.8% for the hedged portfolio).

The more ambitious annual target of 10% should result in a decrease in the portfolio carbon intensity by 47% over 6 years. Results reported in Table 2 suggest that the NZ strategy is effective at reducing carbon intensity (44.2%) and emissions (52%) in 6-year period. This achievement, while remarkable, was largely influenced by the reduction in economic activity during the Covid-19 crisis.

Underpinning the ambitious carbon intensity reduction of the NZ portfolio is a substantial realignment of country weights relative to the BAU benchmark, as illustrated in Table 3. Specifically, with the reduction target of 7.5%, the weights of France and the United Kingdom would increase from 6.9% to 9.9% and from 6.6% to 9.1%, respectively. The weights of Denmark and Sweden also increase by several times, from 0.4%

Table 3 Minimisation of the tracking error: Optimal weights (Consumption per capita metric).

	BAU benchmark	NZ portfolio		
		5% reduction	7.5% reduction	10% reduction
Panel A: Advanced economies	91.07	86.48	82.67	79.38
Australia	1.44	0.52	0.36	0.27
Belgium	1.71	0.11	0.01	0.01
Canada	1.27	1.70	2.15	2.41
Denmark	0.40	3.42	4.71	5.80
France	6.85	9.55	9.87	9.69
Germany	4.76	3.21	3.04	3.08
Italy	6.34	4.65	3.10	2.09
Japan	18.38	17.75	16.74	15.89
Netherlands	1.49	0.03	0.01	0.01
Spain	3.87	3.29	3.06	2.64
Sweden	0.28	6.45	11.05	15.73
United Kingdom	6.58	8.14	9.12	10.01
United States	37.71	27.67	19.47	11.76
Panel B: Emerging economies	8.93	13.52	17.33	20.62
Argentina	0.02	0.01	0.01	0.01
Brazil	0.84	0.19	0.04	0.02
Chile	0.08	0.98	1.55	2.09
China	3.08	3.56	3.81	4.12
Colombia	0.22	0.10	0.12	0.10
Czech Republic	0.14	0.10	0.08	0.06
Dominican Republic	0.01	0.01	0.01	0.01
Hungary	0.15	0.17	0.23	0.27
India	1.39	1.80	2.03	2.19
Indonesia	0.45	0.31	0.16	0.11
Malaysia	0.24	0.51	0.64	0.74
Mexico	0.58	2.59	4.26	5.74
Peru	0.09	0.54	0.70	0.81
Philippines	0.01	0.12	0.12	0.12
Poland	0.38	0.03	0.02	0.02
Romania	0.10	0.05	0.02	0.02
Russia	0.25	0.12	0.07	0.04
South Africa	0.37	0.11	0.04	0.02
Thailand	0.31	1.85	2.93	3.62
Turkey	0.21	0.07	0.03	0.02
Uruguay	0.01	0.32	0.45	0.51

Note: This table reports the average weight of each country in the BAU benchmark and the NZ portfolios with 5%, 7.5%, and 10% reduction targets. The period is 2016–2021.

to 4.7% and from 0.3% to 11.1% respectively. In contrast, the U.S. weight would be reduced from 37.7% to 19.5%.

For emerging economies, the reallocation process resulted in even more substantial shifts. For instance, Mexico's weight would surge from 0.6% to 4.3% and the Thailand's weight would escalate from 0.3% to 2.9%, prompting concerns about these countries' ability to issue additional government bonds without jeopardising debt sustainability. Conversely, Poland's weight is drastically diminished from 0.4% to nearly zero due to its relatively high emissions per capita. Several other countries, including Brazil, Indonesia, Russia, and South Africa, are also nearly excluded from the NZ portfolio to achieve the targeted portfolio-level carbon intensity while keeping the portfolio's credit rating unchanged. It is noteworthy that the total weight of emerging economies represents 8.9% of the BAU benchmark, reflecting the relatively smaller size of their debt compared to their advanced economies counterparts. In the NZ portfolio with 7.5% target, the weight of the emerging economies segment increases to 17.3%, despite the constraint that the credit rating of the portfolio remains consistent with that of the BAU benchmark.

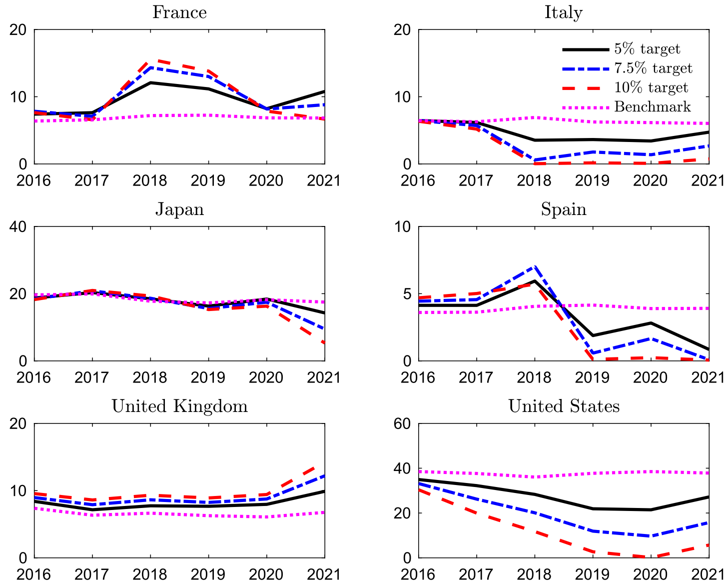
Figure 4 allows us to visualise the evolution of the optimal weights of selected countries in the portfolio (Panel A for advanced economies and Panel B for emerging economies). This figure demonstrates that the 10% target would require an extreme (quite unrealistic) rebalancing, notably from 2019 onward, penalising some countries such as Italy and the United States. Among emerging economies, some countries, such as Chile, Mexico, and Thailand, are massively overweighted in the NZ portfolios.

The figure suggests that the restructuring of both advanced economies and emerging market segments of the portfolio would undergo significant changes as decarbonisation policies continue to expand. Given the lower consumption-based carbon intensity in certain emerging economies, these countries may experience substantial overweighting. Ultimately, the rebalancing of emerging markets plays a crucial role in contributing significantly to the overall decarbonisation process. For instance, in the case of the 7.5% reduction target, the carbon intensity reduction amounts to 23.4% over 6 years within the emerging markets segment (with their weight in the NZ portfolio increasing from 8.9% to 20.6%), and 26.8% in the advanced economies segment.

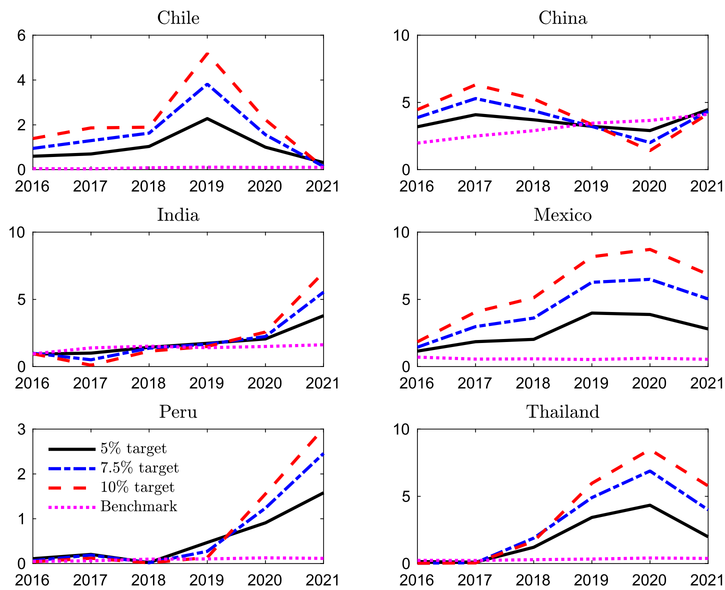
4.2 Baseline analysis with weight constraints

This first part of the analysis highlights three primary observations. First, a substantial decrease in the carbon emissions financed by the portfolio can be accomplished within a 6-year period (up to 52% with the 10% target), even when the benchmark itself undergoes only marginal decarbonisation. Second, the reduction in carbon emissions is achieved with minimal financial repercussions. Third, accomplishing the reduction in carbon emissions necessitates a radical adjustment of the optimal portfolio, leading to significant over- and under-weighting of specific major countries, resulting in a substantial tracking error.

The massive reallocation implied by this analysis prompts several concerns. Executing such a radical rebalancing of weights could pose practical challenges for investors, potentially making it difficult to exclude certain countries entirely from a diversified portfolio. This may encounter political resistance or expose the portfolio to considerable currency risks that may be challenging to hedge comprehensively. For instance, in the scenario with a carbon intensity reduction target of 10% per year, investors would need to reduce their average holdings of U.S. sovereign debt to 11.8%



Panel A: Advanced economies

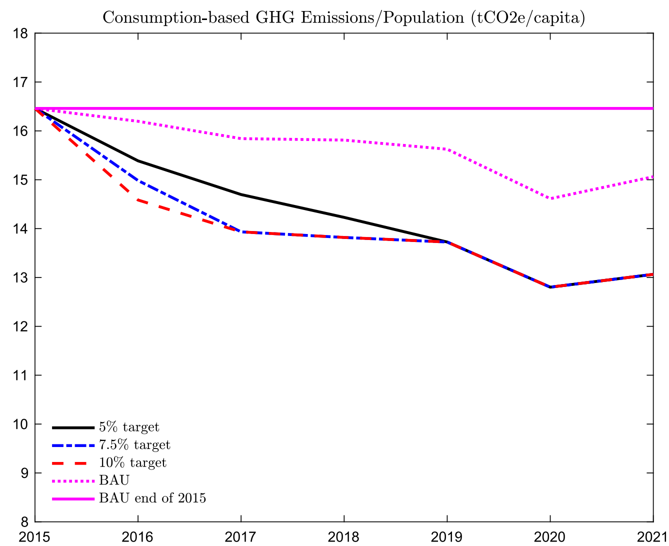


Panel B: Emerging market economies

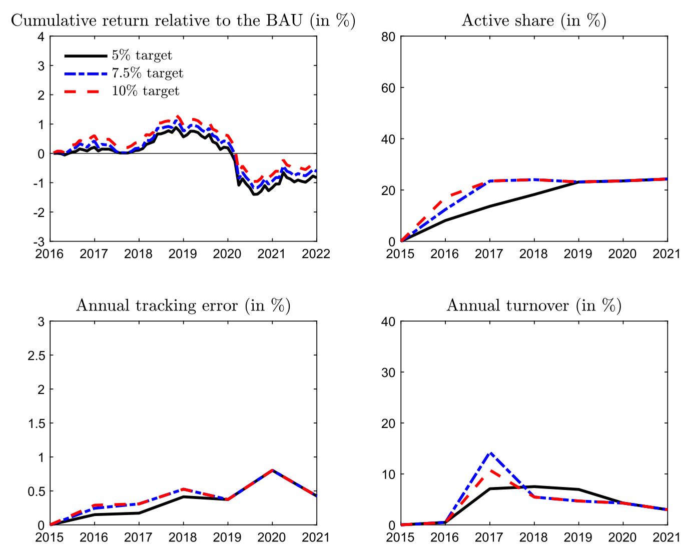
Figure 4 Minimisation of the tracking error: Optimal weights (Consumption per capita metric)

This figure displays the optimal weights of a selection of countries in the various portfolios: the NZ portfolios with 5% (in black), 7.5% (in blue), and 10% (in red) reduction targets and the BAU benchmark (in magenta). Panel A and Panel B correspond to advanced economies and emerging market economies, respectively.

from the initial 37.7%. This would likely be unacceptable for some institutional investors given the status of U.S. Treasuries as safe assets. Moreover, this rebalancing may entail macro-financial risks, such as a significant increase in sovereign yields for the countries whose debt is divested, potentially affecting the average rating or duration of the portfolio.



Panel A: Consumption-based carbon emissions per capita



Panel B: Financial Performance

Figure 5 Minimisation of the tracking error with constraints: Portfolio performance (Consumption per capita metric)

Panel A of this figure displays the consumption-based carbon emissions per capita of the various portfolios: the NZ portfolios with 5% (in black), 7.5% (in blue), and 10% (in red) reduction targets and the BAU benchmark (in magenta). Panel B reports financial performance measures: the cumulative return relative to the BAU benchmark (monthly returns from 2016 to 2021), the active share, the annual tracking error, and the annual turnover. The weights are capped from falling below 50% or surging above 150% relative to the BAU benchmark weight.

To address these concerns, we impose additional restrictions on country weights in the composition of decarbonised portfolios. As an illustration, we consider a scenario in which the weight of any country is restricted from dropping below 50% or exceeding 150% relative to the benchmark weight. This restriction ensures that no country is entirely excluded from the decarbonised portfolio. At the same time, we keep the overall constraint for the NZ portfolio to retain the same creditworthiness as the BAU benchmark.

Results are graphically represented in Figure 5, with further details provided in Table 4. In comparison with the NZ portfolio in the unconstrained scenario (Figure 3), the constrained NZ portfolio, while still outperforming the BAU benchmark in terms of decarbonisation, exhibits limitations due to imposed constraints on weight adjustments. Specifically, the more ambitious decarbonisation targets of 7.5% and 10% cannot be realised over a long period of time. The decarbonisation paths converge after 2019. The NZ portfolio achieves, at best, a cumulative reduction of 20.6% in carbon intensity over 6 years and across different annual rates of decarbonisation. This finding underscores that a heightened annual reduction rate cannot be necessarily translated into a proportionally greater cumulative decarbonisation, given the constrained availability of sovereign bonds for weight adjustments.

As Table 5 demonstrates, the reweighting process in the constrained scenario is much smoother compared to the unconstrained counterpart. In fact, the primary effect of these constraints is the convergence of the aggregate weights of advanced economies and emerging economies toward their respective benchmark weights. Consequently, the reallocation proves advantageous for advanced economies but disadvantageous for emerging economies. In addition, among advanced economies, the portfolio tends to overweight larger economies with intermediary levels of carbon intensity. For instance, under the 7.5% decarbonisation target, Japan and Germany receive higher allocations in the constrained allocation compared to the unconstrained scenario. In contrast, the weight adjustments for Denmark and Sweden are not as pronounced as observed in the unconstrained case. Turning to emerging economies, the portfolio weights for most countries align more closely with the benchmark weights. Notably, the weights of Chile, Mexico, and Thailand are dramatically reduced. The optimal weights of selected countries are reported in Figure 6 for advanced economies (Panel A) and emerging economies (Panel B). The figure illustrates that allocations are much less extreme, which institutional investors may find more manageable for implementation.

Concerning the financial performance of the constrained NZ portfolio, as detailed in Table 4, the annual returns and the Sharpe ratio exhibit very limited decreases relative to the BAU benchmark. However, as expected, we find a reduction in tracking error, turnover, and active share compared to the unconstrained NZ portfolio.

Restricting the span of country weight changes in particular limits the contribution of reweighting across emerging economies issuers to the decarbonisation process. The reduction in the carbon intensity of the emerging and advanced economies segments is equal to 19% and 19.3%, respectively.

Imposing constraints on the extent of changes in country weights, particularly curbing the amplitude of reweighting across emerging economies issuers, has a tangible impact on the contribution of the reweighting process to the overall decarbonisation endeavour. Consequently, the reduction in carbon intensity for both the emerging and advanced economies segments is constrained to approximately 23.4% and 26.8%, respectively.

4.3 Production-based measure of GHG emissions

We have presented our baseline decarbonisation strategy using the consumption-based carbon intensity metric. Now, we consider the

Table 4 Minimisation of the tracking error with constraints: Portfolio performance (Consumption per capita metric).

	BAU benchmark	NZ portfolio		
		5% reduction	7.5% reduction	10% reduction
Panel A: General performance				
Annual active share	—	18.5%	21.8%	22.6%
Annual turnover	0.0%	5.8%	6.3%	5.6%
Sum AE weights	91.1%	90.6%	90.7%	90.7%
Average rating	AA-	AA-	AA-	AA-
Change in GHG intensity	−8.5%	−20.6%	−20.6%	−20.6%
Change in GHG emissions	25.4%	−5.4%	−5.3%	−5.1%
Panel B: Performance of hedged portfolio				
Annual return	3.28%	3.16%	3.19%	3.22%
Annual volatility	3.23%	3.17%	3.17%	3.17%
Ex post Sharpe Ratio	1.02	1.00	1.01	1.02
Annual tracking error	—	0.45%	0.49%	0.50%
Panel C: Performance of unhedged portfolio				
Annual return	2.99%	2.74%	2.78%	2.79%
Annual volatility	5.04%	5.33%	5.43%	5.50%
Ex post Sharpe Ratio	0.59	0.51	0.51	0.51
Annual tracking error	—	0.65%	0.76%	0.79%

Note: Panel A of this table reports some characteristics of the BAU benchmark and the NZ portfolios with 5%, 7.5%, and 10% reduction targets: the average annual share, the annual turnover, the sum of weights in advanced economies, the average rating, and the change in carbon intensity and emissions. Panels B and C report financial performance of the hedged and unhedged portfolios, the annual return and volatility, the ex-post Sharpe ratio, and the annual tracking error. The period is 2016–2021.

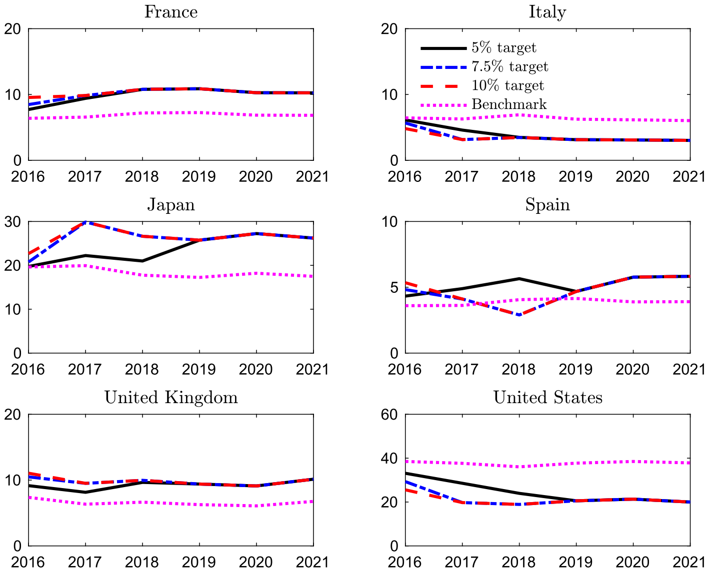
production-based carbon intensity as an alternative metric. The key outcomes of this analysis are depicted in Figure 7, while the financial performance of both the benchmark and optimal portfolios is detailed in Table 6. Furthermore, Table 7 reports the weights of the benchmark and optimal portfolios.

First, as outlined in Table 6, the carbon intensity of the BAU benchmark undergoes a reduction. This reduction is attributed to the collective efforts of most countries in curbing carbon emissions, and its magnitude surpasses that observed with the consumption-based metric. Second, the decarbonisation of the NZ portfolio closely aligns with the targeted reductions of 5%, 7.5%, and 10%. Ex post, the annual reduction stands at 5.5%, 8%, and 10.5%, respectively. This suggests that countries with higher portfolio weights, particularly those with lower carbon intensity, have successfully managed to decrease their carbon intensity over the specified time frame. Overall, the NZ portfolio can also achieve significantly stronger decarbonisation; the cumulative decarbonisation reaches 28.7%, 39.3% and 48.5% with the three annual targets. Total emissions

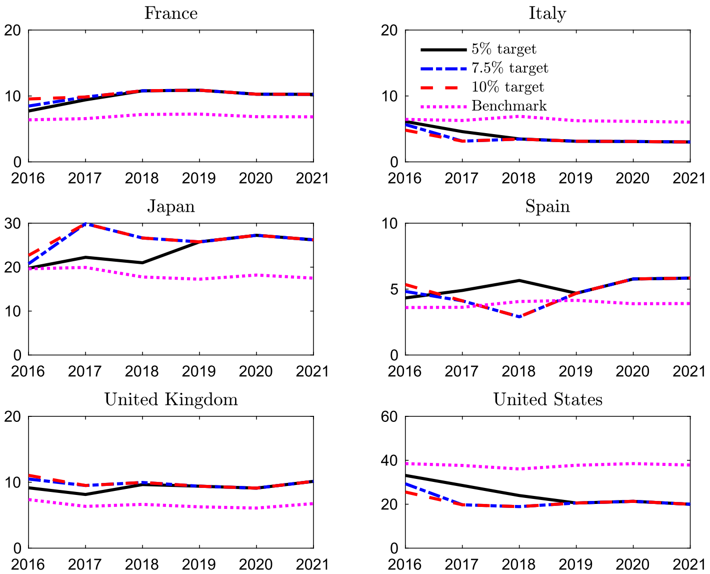
Table 5 Minimisation of the tracking error with constraints: Optimal weights (Consumption per capita metric).

	BAU benchmark	NZ portfolio		
		5% reduction	7.5% reduction	10% reduction
Panel A: Advanced economies	91.07	90.59	90.71	90.74
Australia	1.44	1.99	2.13	2.15
Belgium	1.71	0.86	0.86	0.86
Canada	1.27	1.80	1.84	1.89
Denmark	0.40	0.51	0.55	0.59
France	6.85	9.88	10.08	10.26
Germany	4.76	7.07	7.12	7.13
Italy	6.34	3.91	3.59	3.44
Japan	18.38	23.70	26.08	26.40
Netherlands	1.49	1.42	1.94	1.94
Spain	3.87	5.20	4.69	4.77
Sweden	0.28	0.42	0.42	0.42
United Kingdom	6.58	9.27	9.77	9.86
United States	37.71	24.58	21.64	21.02
Panel B: Emerging economies	8.93	9.41	9.29	9.26
Argentina	0.02	0.01	0.01	0.01
Brazil	0.84	0.45	0.43	0.43
Chile	0.08	0.11	0.11	0.11
China	3.08	4.60	4.60	4.61
Colombia	0.22	0.22	0.22	0.22
Czech Republic	0.14	0.19	0.19	0.19
Dominican Republic	0.01	0.01	0.01	0.01
Hungary	0.15	0.13	0.10	0.10
India	1.39	1.00	1.11	1.10
Indonesia	0.45	0.45	0.39	0.39
Malaysia	0.24	0.22	0.19	0.18
Mexico	0.58	0.69	0.69	0.69
Peru	0.09	0.12	0.12	0.12
Philippines	0.01	0.01	0.01	0.01
Poland	0.38	0.25	0.23	0.25
Romania	0.10	0.06	0.06	0.06
Russia	0.25	0.16	0.15	0.14
South Africa	0.37	0.26	0.20	0.20
Thailand	0.31	0.34	0.34	0.34
Turkey	0.21	0.12	0.11	0.11
Uruguay	0.01	0.01	0.01	0.01

Note: This table reports the average weight of each country in the BAU benchmark and the NZ portfolios with 5%, 7.5%, and 10% reduction targets. The weights are capped from falling below 50% or surging above 150% relative to the benchmark weight. The period is 2016–2021.



Panel A: Advanced economies

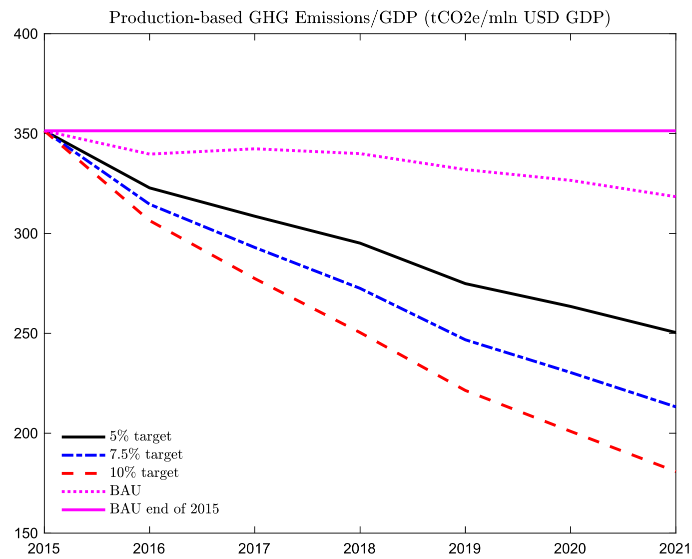


Panel B: Emerging market economies

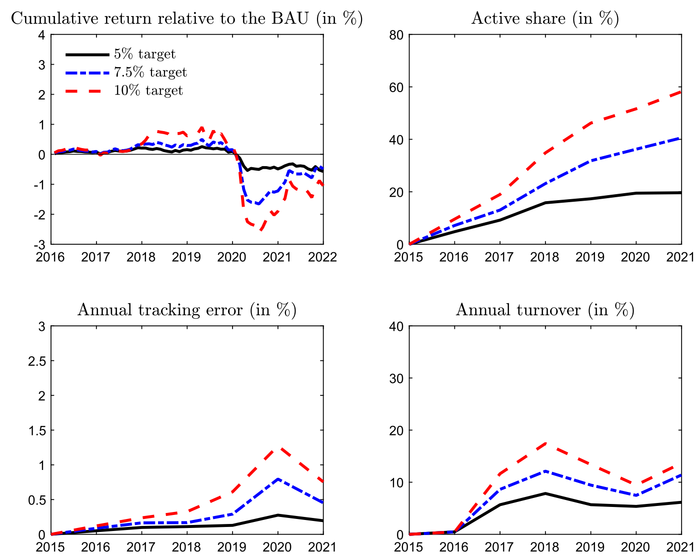
Figure 6 Minimisation of the tracking error with constraints: Optimal weights (Consumption per capita metric).
This figure displays the optimal weights of a selection of countries in the various portfolios: the NZ portfolios with 5% (in black), 7.5% (in blue), and 10% (in red) reduction targets and the BAU benchmark (in magenta). Panel A and Panel B correspond to advanced economies and emerging market economies, respectively. The weights are capped from falling below 50% or surging to 150% relative to the benchmark weights.

experience a slight increase with the 5% target (3.9%) and a more substantial decrease with the 7.5% and 10% targets (−26.9% and −60.8%, respectively).

Regarding the financial performance of the NZ portfolio, Table 6 demonstrates that the cost associated with portfolio decarbonisation remains at a moderate level. First, the Sharpe ratio is



Panel A: Production-based carbon emissions per GDP



Panel B: Financial performance

Figure 7 Minimisation of the tracking error: Portfolio performance (Production per GDP metric).

Panel A of this figure displays the production-based carbon emissions per GDP of the various portfolios: the NZ portfolios with 5% (in black), 7.5% (in blue), and 10% (in red) reduction targets and the BAU benchmark (in magenta). Panel B reports financial performance measures: the cumulative return relative to the BAU benchmark (monthly returns from 2016 to 2021), the active share, the annual tracking error, and the annual turnover.

slightly lower than that of the BAU benchmark. Second, across all reduction targets, the active share and the turnover are similar to the values obtained with the consumption-based metric. In addition, the annual tracking error remains below 1% and is lower than that observed with the consumption-based measure. The primary reason for this reduced tracking error is that the production-based metric favours advanced economies. Given their relatively high weight in

Table 6 Minimisation of the tracking error: Portfolio performance (Production per GDP metric).

	BAU benchmark	NZ portfolio		
		5% reduction	7.5% reduction	10% reduction
Panel A: General performance				
Annual active share	—	14.4%	25.3%	36.6%
Annual turnover	0.0%	6.1%	9.8%	13.1%
Sum AE weights	91.1%	94.5%	96.4%	97.3%
Average rating	AA-	AA-	AA-	AA-
Change in GHG intensity	−8.5%	−28.7%	−39.3%	−48.5%
Change in GHG emissions	25.4%	3.9%	−26.9%	−60.8%
Panel B: Performance of hedged portfolio				
Annual return	3.28%	3.20%	3.21%	3.13%
Annual volatility	3.23%	3.21%	3.18%	3.15%
Ex post Sharpe ratio	1.02	1.00	1.01	1.00
Annual tracking error	—	0.17%	0.42%	0.69%
Panel C: Performance of unhedged portfolio				
Annual return	2.99%	2.59%	2.52%	2.30%
Annual volatility	5.04%	5.25%	5.48%	5.85%
Ex post Sharpe ratio	0.59	0.49	0.46	0.39
Annual tracking error	—	0.40%	0.82%	1.51%

Note: Panel A of this table reports some characteristics of the BAU benchmark and the NZ portfolios with 5%, 7.5%, and 10% reduction targets: the average annual share, the annual turnover, the sum of weights in advanced economies, the average rating, and the change in carbon intensity and emissions. Panels B and C report financial performance of the hedged and unhedged portfolios, the annual return and volatility, the ex-post Sharpe ratio, and the annual tracking error. The period is 2016–2021.

the J.P. Morgan index, reallocating the portfolio and reducing its carbon emissions can be achieved with a limited impact on portfolio weights. Interestingly, Figure 7 illustrates a substantial increase in tracking error in 2020, even with the 5% emissions reduction target. This can be attributed to the marginal decrease in benchmark emissions during the Covid-19 crisis (by 3.9% when measured by the production-based carbon intensity), intensifying the burden of achieving a reduction in carbon emissions.

As expected, the reallocation process is more radical for emerging economies than for advanced economies in this scenario. This distinction arises due to the considerably higher carbon intensity and greater variability in emissions observed among emerging economies. Consequently, the weight assigned to most emerging economies experience substantial reductions, leading to an overall weight of emerging economies diminishing to 3.6% with a 7.5% emissions reduction target. In the unconstrained scenario, various emerging economies, including India, Russia, and South Africa, are entirely excluded from the NZ portfolio, as their emissions exceed 1,000 tons of CO_2 per million U.S. dollars of GDP annually over the sample period. In contrast, countries with lower emissions (below 500 tons of CO_2 per million U.S. dollars of GDP), such as the Dominican Republic, Hungary, and Peru, receive significantly higher weights. Regarding

Table 7 Minimisation of the tracking error: Optimal weights (Production per GDP metric).

	BAU benchmark	NZ portfolio		
		5% reduction	7.5% reduction	10% reduction
Panel A: Advanced economies	91.07	94.51	96.38	97.28
Australia	1.44	0.67	0.45	0.27
Belgium	1.71	0.69	0.72	0.68
Canada	1.27	0.59	0.30	0.12
Denmark	0.40	2.68	3.22	3.01
France	6.85	6.10	3.79	2.85
Germany	4.76	0.85	0.40	0.19
Italy	6.34	6.52	8.09	9.54
Japan	18.38	21.85	24.43	26.18
Netherlands	1.49	1.75	0.78	0.57
Spain	3.87	4.88	4.51	3.60
Sweden	0.28	3.64	9.86	16.92
United Kingdom	6.58	6.74	8.33	10.08
United States	37.71	37.54	31.49	23.26
Panel B: Emerging economies	8.93	5.49	3.62	2.72
Argentina	0.02	0.07	0.06	0.05
Brazil	0.84	0.49	0.19	0.11
Chile	0.08	0.28	0.09	0.05
China	3.08	0.52	0.18	0.09
Colombia	0.22	0.43	0.15	0.06
Czech Republic	0.14	0.02	0.00	0.01
Dominican Republic	0.01	0.02	0.39	0.28
Hungary	0.15	1.83	1.44	1.04
India	1.39	0.28	0.05	0.01
Indonesia	0.45	0.16	0.11	0.08
Malaysia	0.24	0.01	0.01	0.00
Mexico	0.58	0.48	0.29	0.29
Peru	0.09	0.07	0.29	0.35
Philippines	0.01	0.01	0.01	0.01
Poland	0.38	0.01	0.01	0.01
Romania	0.10	0.41	0.06	0.02
Russia	0.25	0.03	0.02	0.01
South Africa	0.37	0.00	0.00	0.00
Thailand	0.31	0.01	0.00	0.00
Turkey	0.21	0.33	0.26	0.26
Uruguay	0.01	0.01	0.00	0.00

Note: This table reports the average weight of each country in the BAU benchmark and the NZ portfolios with 5%, 7.5%, and 10% reduction targets. The period is 2016–2021.

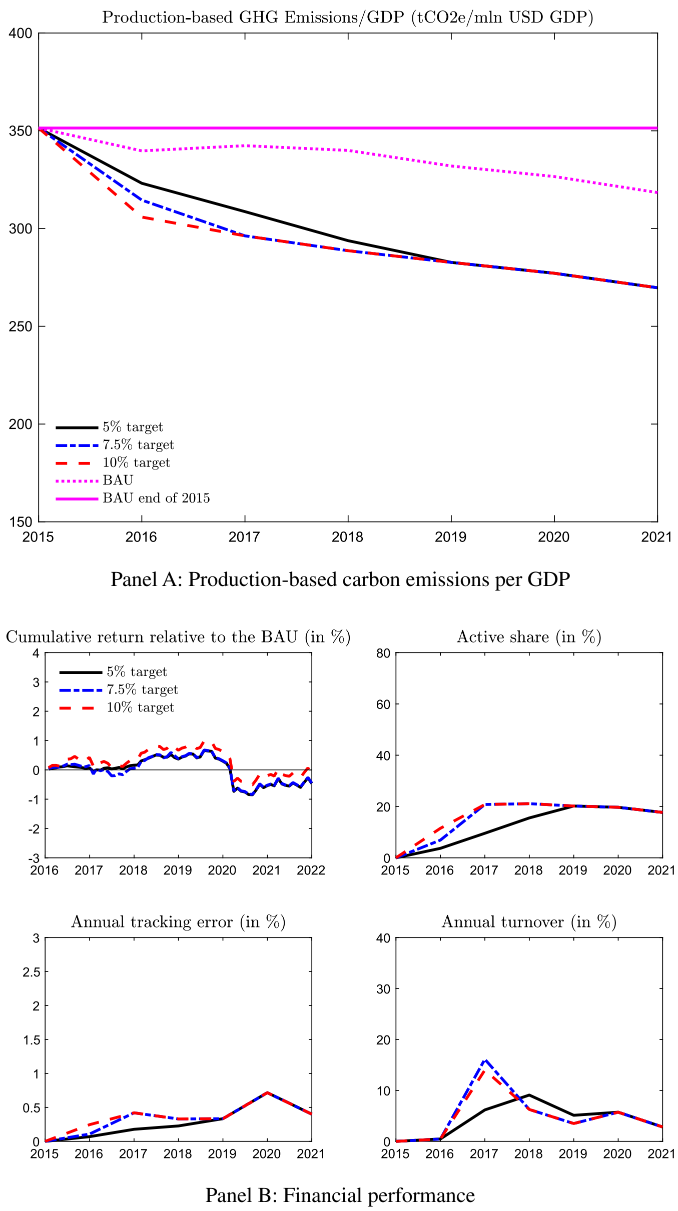


Figure 8 Minimisation of the tracking error with constraints: Portfolio performance (Production per GDP metric).

Panel A of this figure displays the production-based carbon emissions per GDP of the various portfolios: the NZ portfolios with 5% (in black), 7.5% (in blue), and 10% (in red) reduction targets and the BAU benchmark (in magenta). Panel B reports financial performance measures: the cumulative return relative to the BAU benchmark (monthly returns from 2016 to 2021), the active share, the annual tracking error, and the annual turnover.

advanced economies, certain countries (Belgium, Italy, the United States), which previously had lower weights with the consumption-based carbon intensity metric, are less penalised with the production-based intensity metric.

When we further impose restrictions on the magnitude of changes in country weights, similar to the constrained optimisation in the baseline, a substantial reduction in the tracking error and active share of the NZ portfolio is achieved, albeit

Table 8 Minimisation of the tracking error with constraints: Portfolio performance (Production per GDP metric).

	BAU benchmark	NZ portfolio		
		5% reduction	7.5% reduction	10% reduction
Panel A: General performance				
Annual active share	—	14.4%	17.7%	18.5%
Annual turnover	0.0%	5.8%	6.9%	6.5%
Sum AE weights	91.1%	95.2%	95.4%	95.5%
Average rating	AA-	AA-	AA-	AA-
Change in GHG intensity	−8.5%	−23.3%	−23.3%	−23.3%
Change in GHG emissions	25.4%	−7.6%	−7.6%	−7.3%
Panel B: Performance of hedged portfolio				
Annual return	3.28%	3.22%	3.22%	3.27%
Annual volatility	3.23%	3.27%	3.29%	3.30%
Ex post Sharpe ratio	1.02	0.98	0.98	0.99
Annual tracking error	—	0.38%	0.42%	0.43%
Panel C: Performance of unhedged portfolio				
Annual return	2.99%	2.72%	2.78%	2.76%
Annual volatility	5.04%	5.38%	5.46%	5.48%
Ex post Sharpe ratio	0.59	0.51	0.51	0.50
Annual tracking error	—	0.54%	0.64%	0.66%

Note: Panel A of this table reports some characteristics of the BAU benchmark and the NZ portfolios with 5%, 7.5%, and 10% reduction targets: the average annual share, the annual turnover, the sum of weights in advanced economies, the average rating, and the change in carbon intensity and emissions. Panels B and C report financial performance of the hedged and unhedged portfolios, the annual return and volatility, the ex-post Sharpe ratio, and the annual tracking error. The weights are capped from falling below 50% or surging above 150% relative to the benchmark weight. The period is 2016–2021.

at the expense of a less impactful decarbonisation. Figure 8 reports the results when the weight of any country is restricted from falling below 50% or exceeding 150% relative to the benchmark. The decarbonisation is saturated after 2 years despite the annual decarbonisation targets. Table 8 shows that the three annual decarbonisation targets result in the same cumulative reduction in carbon intensity of 23.2% over 6 years. Additionally, annual returns and volatilities slightly surpass those observed in the constrained baseline scenario. As anticipated, our findings reveal less pronounced allocations, particularly concerning emerging economies. Notably, with the 7.5% emissions reduction target, we achieve an annual tracking error below 0.5% and a reduction in the annual active share to approximately 16%.

Table 9 further reports the weights of the benchmark and optimal portfolios. As expected, we find much less extreme allocations, notably for emerging economies. Importantly, we reduce the annual active share close to 20% and the annual tracking error below 0.7%. However, the reduction in the carbon intensity of the portfolio does not exceed 18% even with an ex ante 10% reduction target.

Table 9 Minimisation of the tracking error with constraints: Optimal weights (Production per GDP metric).

	BAU benchmark	NZ portfolio		
		5% reduction	7.5% reduction	10% reduction
Panel A: Advanced economies	91.07	95.17	95.38	95.49
Australia	1.44	0.90	0.82	0.76
Belgium	1.71	1.49	1.88	1.87
Canada	1.27	0.66	0.64	0.64
Denmark	0.40	0.58	0.59	0.59
France	6.85	9.77	10.10	10.26
Germany	4.76	5.31	6.39	6.42
Italy	6.34	6.50	6.39	6.45
Japan	18.38	24.03	25.44	25.64
Netherlands	1.49	2.04	2.04	2.01
Spain	3.87	4.23	3.98	3.98
Sweden	0.28	0.42	0.42	0.42
United Kingdom	6.58	9.01	9.46	9.84
United States	37.71	30.24	27.21	26.62
Panel B: Emerging economies	8.93	4.83	4.62	4.51
Argentina	0.02	0.01	0.01	0.01
Brazil	0.84	0.49	0.43	0.42
Chile	0.08	0.05	0.05	0.05
China	3.08	1.56	1.54	1.54
Colombia	0.22	0.13	0.14	0.11
Czech Republic	0.14	0.07	0.07	0.07
Dominican Republic	0.01	0.00	0.00	0.00
Hungary	0.15	0.12	0.10	0.08
India	1.39	0.70	0.69	0.69
Indonesia	0.45	0.26	0.23	0.22
Malaysia	0.24	0.12	0.12	0.12
Mexico	0.58	0.36	0.32	0.30
Peru	0.09	0.06	0.05	0.05
Philippines	0.01	0.01	0.01	0.01
Poland	0.38	0.19	0.19	0.19
Romania	0.10	0.06	0.05	0.05
Russia	0.25	0.13	0.13	0.13
South Africa	0.37	0.19	0.19	0.19
Thailand	0.31	0.16	0.16	0.16
Turkey	0.21	0.15	0.13	0.11
Uruguay	0.01	0.01	0.00	0.00

Note: This table reports the average weight of each country in the BAU benchmark and the NZ portfolios with 5%, 7.5%, and 10% reduction targets. The weights are capped from falling below 50% or surging above 150% relative to the benchmark weight. The period is 2016–2021.

5 Policy Implications and Conclusion

In this paper, we present a strategy aimed at assisting investors in mitigating the carbon footprint associated with their sovereign securities portfolios. Employing a specifically tailored per capita metric for carbon emissions, we demonstrate that the process of portfolio decarbonisation, involving the redistribution of funds from sovereign securities of high-emitting countries to those of low-emitting countries, can result in a substantial reduction in the overall carbon footprint of a sovereign portfolio.

Investors could have achieve a substantial reduction of nearly 35% in the carbon intensity of a global sovereign portfolio from the end of 2015 to 2021, implementing an annual 7.5% reduction target consistently for 6 years. Remarkably, this reduction could be predominantly realised through a profound reallocation of the portfolio in favour of low-carbon economies, with limited adverse effects on its financial performance. The creditworthiness of the NZ portfolio remains as strong as the BAU benchmark, at AA-. To address investors' concerns regarding significant fluctuations in sovereign issuers' weights within a portfolio, we imposed constraints by setting upper and lower bounds for changes in country weights and mandating the NZ portfolio to maintain an equivalent credit rating as the BAU benchmark. While these constraints curtailed the overall carbon intensity reduction potential of the NZ portfolio to 21% over 6 years instead of 35%, the NZ portfolio continued to outperform the BAU benchmark. The simplicity of the strategy proposed in this paper renders it easily implementable, even by otherwise passive investors.

Several important caveats should be considered in our analysis. First, our assumption that investors function as price takers may warrant scrutiny. If a substantial portion of investors were to adopt the proposed approach, it could potentially influence the financing costs of sovereign issuers. Given the considerable scale of the Glasgow Net Zero Alliance portfolio, the implementation of our NZ investment strategy, or similar strategies, is likely to have repercussions on the issuing conditions of sovereigns. However, a comprehensive examination of this impact falls beyond the scope of our present study and could be the subject of subsequent research. Second, our analysis relies on past carbon reduction efforts by countries and overlooks forward-looking commitments made by sovereign issuers. This approach may disadvantage countries whose endeavours to curtail carbon emissions are anticipated to materialise in the medium term. It is crucial to note, though, that any country demonstrating a more substantial reduction in carbon emissions than others will see an increasing share in our NZ portfolio as soon as data on the reduction become observable.

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Endnotes

1 A precise definition is provided by the United Nations from an international perspective (see https://www.un.org/en/climatechange/net-zero-coalition).

[2] In this study, we propose three scenarios with different annual decarbonisation targets of 5%, 7.5%, and 10%, respectively.

[3] See https://www.unpri.org/investment-tools/fixed-income/sovereign-debt/ascor-project.

[4] There are several variants within the categories of the GBI Global and GBI EM indices. For instance, the GBI Global has a variant, GBI Broad, which includes 27 countries and partly overlaps with the GBI EM Broad (for instance, Czech Republic, Mexico, Poland, and South Africa are constituents of both indices). To keep the portfolio of advanced economies and emerging economies mutually exclusive, we do not use the GBI Broad in our analysis. Similarly, the GBI EM has a more restrictive version, excluding countries with explicit capital controls, specifically China and India. To include these large issuers and GHG emitters, we use the GBI EM Broad. Note also that we do not rely on another widely used sovereign bond index, J.P. Morgan Emerging Markets Bond Index (EMBI), for two reasons. First, the EMBI tracks U.S. dollar debt instruments issued by sovereign entities in emerging market economies. However, emerging market economies have significantly reduced their dependence on foreign currency financing and have turned to local currency borrowing in domestic and international debt markets (see Cheng, 2021). Moreover, given that advanced economies mostly issue local-currency bonds, we need to retain the same perimeter so that we can construct a consistent BAU benchmark across advanced economies and emerging market economies.

[5] A third approach, a hybrid of the production-based and consumption-based methods, considers emissions generated by both production (including exports) and imports. While reflective of the overall carbon dependence of the economy, this approach introduces some additional double counting. We have constructed such an NZ portfolio, with results available upon request.

[6] The ownership approach is akin to the carbon footprint measure often used for equity or corporate bond portfolios.

[7] This assumption is reasonable due to the high persistence in carbon measures, alleviating the need for intra-year rebalancing complexities.

[8] Alternative measures of the covariance matrix may be considered, for instance based on an exponentially weighted moving average or a factor model.

[9] See EU members' emission targets https://ec.europa.eu/clima/eu-action/effort-sharing-member-states-emission-targets_en.

[10] See UNFCCC NDC synthesis reports, for instance the 2022 version: https://unfccc.int/ndc-synthesis-report-2022. See also Bolton *et al.* (2022).

[11] This increase is primarily due to a combination of three factors affecting China and India: the increase in their population, the increase of their weight in the J.P. Morgan index, and, to a lesser extent, the increase in their per-capita carbon emissions.

[12] Unless otherwise indicated, we report returns that are hedged against currency risks.

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