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# Building portfolios of sovereign securities with decreasing carbon footprints*

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**Abstract**

We propose a strategy to build portfolios of sovereign securities with progressively declining carbon footprints. Passive investors could use it as a new Paris-consistent benchmark to construct a "net zero" (NZ) portfolio while tracking closely the risk-adjusted returns of a business-as-usual (BAU) benchmark. Our strategy rewards sovereign issuers that have made stronger efforts in reducing carbon intensity, measured by total domestic emissions per capita. The NZ portfolio would have reduced carbon intensity by 41% between 2014 and 2019, by assigning higher weights to countries that have had lower carbon emissions. Among advanced economies, rebalancing leads to raising shares of France, Italy and Spain in the portfolio at the expense of the United States. And among emerging market economies, this leads to higher shares for Chile, the Philippines and Romania at the expense of China. Importantly, the NZ portfolio retains the same creditworthiness as the BAU benchmark without entailing materially higher foreign exchange risks.

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**Keywords:** Carbon footprints; sovereign debt; portfolio rebalancing; portfolio optimisation; active share; tracking error.

# 1 Introduction

Portfolio investors are increasingly seeking ways to reduce carbon footprints of their portfolios. Many investors have already started to report the Greenhouse Gas (GHG) emissions associated with a portfolio's underlying holdings of listed equities and corporate bonds. However, even though sovereign bonds represent one of the largest asset classes and a significant percentage of diversified investment portfolios, especially among institutional investors, little has been done as regards greening investors' portfolios of sovereign securities.

In this paper, we show how investors can green portfolios of sovereign securities and report the impact of decarbonisation on relative country weights in a portfolio and the portfolio's financial characteristics (e.g., returns, risks, etc.), with respect to a benchmark.

Investors have both incentives and 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, can be considered to be exposed to greater risks related to the transition to a low-carbon economy. On the other hand, investors' portfolio adjustment is a requirement for green investment and provides incentives for sovereign issuers to make actions to reduce the carbon emissions of economic activity in their jurisdiction.

Our work shows that investors could build a decarbonised portfolio with 41% of cumulative reduction in carbon intensity over five years by adjusting country weights. This is what we call a "net zero" or NZ portfolio in our paper. In comparison, the benchmark portfolio with unchanged country weights that we name the Business-as-usual (BAU) portfolio can only achieve 14.1% carbon intensity reduction (and 4.3% overall emissions reduction). Annual returns of the NZ portfolio track well those of the BAU benchmark portfolio with slightly higher volatilities. To achieve this ambitious objective of carbon intensity reduction, the rebalancing of country weights in the NZ portfolio is radical. It requires reducing the weights of the United States from 37.6% to 20.8% and consequently increasing those of European countries among advanced economies. As for emerging market economies, investment will shift from Chinese government bonds to sovereign securities from Chile, Romania and the Philippines. This is our first set of results from an unrestricted perspective.

Our analysis continues by adding a number of constraints in the portfolio optimisation and rebalancing exercise. First, investors may dislike too radical changes in country weights with respect to the BAU benchmark. Some countries may be unable to issue much more securities to meet with a suddenly increased demand. For others, given their sheer size in the sovereign fixed income market (e.g., the United States), too large a diversion could disturb the market. We thus impose upper and lower limits to the changes in country weights. This means that at any point, a country's share in the portfolio cannot fall below 50% or exceed 150% relative to its weight in the BAU benchmark. Investors could also be cautious about the impact of the portfolio rebalancing on credit and currency risks. We can thus set a limit on the changes in the overall creditworthiness of the portfolio. And we disentangle the effects on both unhedged and hedged returns[1] to control for changes in currency risks implied by reallocating funds toward greener issuers. The results from our constrained approach successfully reduce large swings in country weights. However, the NZ portfolio under constraints can only achieve 30% cumualtive reduction in carbon intensity, not as high as in the unconstrained case but still much higher than the BAU benchmark.

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, compared to the consensus on carbon disclosure and carbon intensity measures of equities and corporate bonds (Ehlers et al., 2020), many technical problems prevent clarity on methodologies to evaluate sovereign assets' carbon footprints. Domínguez-Jiménez and Lehmann (2021) discuss the definition of the relevant scope of emissions for sovereign bond issuers, namely whether to include emissions from a central government only or to take into account the economy-wide emissions. Related, when looking into the economy-wide emissions, whether the emissions should only focus on those locally produced (from domestic emissions or emissions embodied in exported goods), or locally consumed (domestic emissions and those embodied in trade, netting out exports). Following Burns et al. (2016) and Desme and Smart (2018), we adopt in our baseline analysis a consumption-based carbon emission metric, scaled by population. This metric includes not only carbon emissions that are generated from domestic production, but also those

[1] Unhedged returns are composed of both local market returns from interest rates and currency returns from spot exchange rate fluctuations. Hedged returns, in addition, factor in the returns from a forward contract that aims at mitigating exchange risks.

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 report in the Appendix results based on an alternative measure of carbon intensity, i.e., a production-based carbon emission metric, encompassing both carbon emissions from domestic consumption and exports.

Second, our work is related to the literature on climate risks and portfolio management. The current literature focuses mostly on greening portfolios of private assets, 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 to allow long-term passive investors to hedge climate risks without sacrificing financial returns. Bolton and Kacperczyk (2020) show that investors demand compensation for their exposure to carbon emission risks and exclude high-carbon emitters from investment in a few salient industries. Jondeau et al. (2021) examine strategies for investors to trim the carbon footprint of their portfolios of listed equities. Using the MSCI global stock portfolio of 2010 as a benchmark, the authors show that a passive investor could have cut their portfolios' carbon footprints 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 portfolios' financial returns. Fahlenbrach and Jondeau (2021) propose strategies to green the Swiss National Bank (SNB)'s portfolio. They find that the carbon footprint from the SNB's 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. Giacomo Bressan (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 about 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.

Regarding the methodology that we use for portfolio optimisation, we rely on the prevailing methods used to measure the performance of active fund management in the finance literature. We use the active share as the baseline method for portfolio optimisation, following Cremers and Petajisto (2009) and use the tracking error as an alternative optimisation tool. Petajisto (2013) compares these two optimisation methods and maps out the circumstances to privilege one or the other.

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

## 2 Data

We first need to choose a BAU benchmark portfolio before embarking on the journey of reducing its carbon footprints. For this purpose, we use J.P. Morgan's Government Bond Indices, as these are widely used sovereign fixed-income indices by investors and provide us with financial data at both the aggregate and country levels, together with 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 emerging market debt benchmark and currently includes 21 emerging market economies. It comprises regularly traded, fixed-rate, domestic-currency government bonds, which international investors can buy and sell.[2]

[2] There are several variants within the categories of GBI Global and GBI EM. 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). To keep the portfolio of advanced economies and emerging economies mutually exclusive, we decide not to use GBI Global in our analysis. Similarly, GBI EM has a more restrictive version, excluding countries with explicit capital controls, in

The first set of important variables 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 in the BAU portfolio at the end of 2015 and 2020, namely the start and end years for our portfolio rebalancing exercise later. Total weights in Table 1 (the second and the 6th columns) refer to the shares of countries - advanced and emerging economies altogether - in the indices. Regional weights (the third and the 7th columns) indicate a country's share within one of the two country groupings - advance economies vs emerging economies. For instance, among advanced economies, the United States and Japan have the biggest regional weights, close to 42% and 20% in 2020, respectively. Next in the line are the United Kingdom and France, with their weights above 7.5%. Among emerging economies, countries with the largest regional weights are China (41%) and India (16%). Indonesia, Mexico, and Brazil, with their weights between 5% and 6% of the index, are distant followers.

Second, for our portfolio management, we extract return data from J.P. Morgan indices. All returns used in our analysis are total returns, which include changes in both clean price and accrued interest) converted to U.S. dollars. All coupons received are immediately reinvested into the local market. In addition, J.P. Morgan indices report both returns hedged or unhedged against currency risks. 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 our decarbonised portfolios could entail large swings in assets denominated in different currencies. In our subsequent analysis, we report the financial performance of both hedged and unhedged portfolios. The hedged index is obtained by adjusting the unhedged index with a one-month currency forward contract.

[Insert Table 1 here]

Data related to GHG emissions come from Trucost sovereign environmental database. Additional economic variables that are used to scale GHG emission data for cross-country comparison are extracted from the World Bank World Development Indicators. Following Desme and Smart (2018), we construct metrics of GHG emissions intensity for each of

particular, China and India. In order to include these large issuers and GHG emitters, we decide to use GBI EM Broad.

the countries in J.P. Morgan indices using two approaches: production-based accounting and consumption-based accounting. For practical reasons, governments tend to focus on GHG emissions in a given territory (production-based accounting), regardless of the destination of the goods and services produced. Although this approach is recommended by the Kyoto Protocol, it entails carbon leakages from advanced to emerging economies as the former tend to transfer the most polluting production to other countries with less strict environmental regulations. An alternative approach consists in measuring GHG emissions resulting from domestic final demand, i.e., all the goods and services consumed in a given country, encompassing both emissions produced domestically and from imports (consumption-based accounting, see Desme and Smart, 2018). With this approach, emissions embedded in imports are added to those generated from domestic consumption, while emissions from exports are excluded.

To translate GHG emissions into carbon intensity, we need to scale emissions data and the choice of the denominator must be consistent with the accounting approach. It is natural to standardise production-based emissions, denoted by $E_{i,t}^{(prod)}$, by domestic GDP, as it measures the value of goods and services produced in the given country. We therefore measure carbon intensity in the production-based approach as:

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

GDP is expressed in constant US dollars (2010). The carbon intensity from this approach is expressed in tons of $CO_2$ equivalent per million USD of GDP.

Consumption-based GHG emissions, denoted by $E_{i,t}^{(cons)}$, should be scaled by the country's population to reflect individuals' carbon consumption. The carbon intensity from this approach is defined as:

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

Carbon intensity is expressed in tons of $CO_2$ equivalent per capita.

Both measures of carbon intensity are reported in Table 1 as well. As expected, if we consider the consumption-based carbon intensity, emerging economies' carbon intensity is smaller than advanced economies'. In 2020, the average carbon intensity (weighted by the market weights of the JP Morgan index), is equal to 14.7 tons per capita for advanced economies and 6.7 tons for emerging economies, as shown in Figure 1 (Panels A and B, red dashed lines). The main contributors are Belgium, the United States, and the Netherlands (above 20 tons) among advanced economies and Czech Republic, Malaysia, and Poland (above 10 tons) among emerging economies.

In contrast, advanced economies have lower production-based carbon intensity than their emerging economy peers, as they have more efficient production processes and may have relocated part of the most polluting industries abroad. In 2020, advanced economies registered 254.1 tons per million USD of GDP on average as per the production-based carbon intensity metric and emerging economies generated on average 963.2 tons per GDP, as Figure 1 (Panels C and D, red dashed lines) indicates. Russia and South Africa are the main contributors among emerging economies, whereas Canada, Australia, and the United States are the main advanced economy contributors. We also observe that all advanced economies have reduced their carbon intensity for both consumption-based and production-based measures between 2015 and 2020. Most emerging economies have reduced their production-based intensity but have seen their consumption-based intensity increase, given their economic development which allows people to upgrade their consumption from foreign imports.

[Insert Figure 1 here]

# 3 Methodology and empirical results

## 3.1 Constructing a decarbonised portfolio

Our exercise of building a decarbonised portfolio from a BAU benchmark consists of finding optimal country weight allocation to meet a preset target of carbon intensity. The carbon intensity of a portfolio with weights $\alpha_t^{(p)} = \{\alpha_{1,t}^{(p)}, \cdots, \alpha_{N_t,t}^{(p)}\}$ is given by:

$$CI_{i,t}^{(p)} = \sum_{i=1}^{N_t} \alpha_{i,t}^{(p)} CI_{i,t}, \tag{3}$$

where $CI_{i,t}$ denotes any of the two metrics presented in Section 2 for a country $i$ (production-based or consumption-based). $N_t$ is the number of countries in the portfolio in month

$t$. The investment decision at the end of date $t-1$ is based on information up to that year (financial returns and carbon emissions), with the financial performance of the investment strategy being evaluated at the end of year $t$. $\alpha_{i,t}^{(p)}$ refers to a country $i$'s weight in the portfolio $(p)$.

The investor composes a portfolio to meet the emission reduction target while keeping the portfolio's financial characteristics as close as possible to those of the BAU benchmark. A first measure of closeness with respect to the benchmark portfolio is the active share. As defined by Petajisto (2013), the active share measures the difference between the weights in our decarbonised portfolio and in the benchmark portfolio, namely

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

where $\alpha_{i,t}^{(b)}$ denotes the weight of country $i$ in month $t$ in the BAU benchmark portfolio $(b)$.

An alternative method to track the benchmark, which we discuss in Appendix B, is the tracking error volatility. It calculates the volatility of the difference between the performance of an optimal portfolio (the decarbonised portfolio in our case) and that of a benchmark. It is defined as:

$$TE_t^{(p)} = \sqrt{\frac{1}{60}\sum_{\tau=1}^{60}\left(R_{t-\tau}^{(p)} - R_{t-\tau}^{(b)}\right)^2}, \tag{5}$$

where $R_t^{(p)}$ and $R_t^{(b)}$ denote the weighted average returns of the portfolio and the benchmark in month $t$. The tracking error is computed using the latest five years of monthly returns.

To evaluate the cost of rebalancing the portfolio, we also report the turnover, which measures the change in the portfolio positions. As the weights of the various assets can vary between two rebalancings due to changes in market prices, we measure turnover as follows:

$$TO_t^{(p)} = \frac{1}{2}\sum_{i=1}^{N_t} |\alpha_{i,t}^{(p)} - \alpha_{i,t-}^{(p)}|, \tag{6}$$

where $\alpha_{i,t-}^{(p)}$ denotes the weight of country $i$ just before the rebalancing at date $t$ and is proxied as: $\alpha_{i,t-1}^{(p)}(1+R_i,t)/\sum_{j=1}^{N_t}(1+R_{j,t})$.

We also assume that the investor keeps the same relative weights of advanced economies and emerging economies as in the overall BAU benchmark. This is to avoid a massive reallocation between country groupings, namely from advanced to emerging economies when the consumption-based intensity is used and from emerging to advanced economies when the production-based measure is used. As a consequence, we impose in the minimisation programme that the sum of the weights allocated to advanced economies remains identical to that in the benchmark portfolio.

To summarise our strategy of portfolio rebalancing, we first need to set out a target for carbon intensity reduction, which can be measured using two different carbon intensity metrics: consumption-based GHG emissions per capita (used for the baseline analysis) and production-based GHG emissions per GDP. We privilege the consumption-based approach because it gives stronger incentives for advanced economies to contribute strongly to carbon emission reduction. This is also in line with the ambitious net zero strategy set out by countries in the European Union with quantifiable targets in 2020, 2030 and 2050.[3] The second dimension of our methodology is to use a portfolio optimisation tool to track the BAU benchmark's financial performances. Two strategies are detailed above. In the baseline analysis, we opt the active share method. The diagram in Figure 2 provides an overview of the different scenarios we will examine in the rest of the paper.

[Insert Figure 2 here]

### 3.2 The net zero portfolio under the unrestricted perspective

In our baseline analysis, we set an objective of reducing carbon intensity by 10% per year over five years for the NZ decarbonised portfolio. This is needed to contain carbon emissions under the carbon budget. The investor minimises the squared active share to satisfy this objective of carbon intensity reduction using the consumption-based approach.

Results are reported in Figure 3. Panel A displays the trajectory of the carbon intensity over a five-year window (2016-2020) of the BAU portfolio (magenta dashed line) and the NZ portfolio (black line). The horizontal blue line indicates the carbon

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

intensity of the BAU at the end of 2015, i.e., the starting point for the decarbonisation process.

[Insert Figure 3 here]

We observe that the NZ portfolio reduces carbon intensity in a linear fashion over five years and achieve 41% cumulative carbon intensity reduction. In comparison, the BAU portfolio can only achieve 14.1% carbon intensity reduction with a bumpy trajectory. Between 2017 and 2018, the portfolio's carbon intensity even increases slightly.

Underpinning the ambitious carbon footprint reduction of the NZ portfolio are substantial changes in country weights relative to the BAU portfolio, as Table 2 demonstrates. For instance, the weights of Italy and Spain increased from 6.3% to 11.6% and from 3.9% to 9.7%, respectively. In contrast, the U.S.'s weight is reduced from 37.6% to 20.8%. For emerging economies, rebalancing proved to be even more extreme. The weight of Colombia would increase from 0.23% to 1.31% and the weight of Philippines from 0.01% to 2.25%, raising the concern about these countries' capacity to provide additional government bonds without affecting debt sustainability. In contrast, China's weight is reduced from 3.31% to 0.27% given its relatively high emissions. Note that emerging economies' weights in the portfolios seem very small, this is due to the relative small size of these countries' total debt in comparison with their advanced economies peers. On average, the total weights of the advanced economies and Emerging economies are equal to 90.61% and 9.39% in the portfolios, respectively.

[Insert Table 2 here]

Turning to financial performance, Figure 3 Panel B reports the cumulative returns of the NZ portfolio relative to the BAU, the active share ($AS_t^{(p)}$), the active share ($AS_t^{(p)}$), the annualised tracking error volatility ($TE_t^{(p)}$), and the annualised turnover ($TO_t^{(p)}$), respectively.[4] And Table 3 provides more details. The annualised returns of the NZ portfolio (3.3%) is slightly higher than the BAU benchmark (3.2% on average). However, the annualised tracking error is relatively high (up to 1% on average), indicating higher

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

volatilities associated with portfolio rebalancing. Moreover, annual turnover is below 10%. Overall, these indicators suggests that the cost of decarbonisation is marginal in terms of financial performance.

Table 3 also reports the financial performance of the portfolios without hedging. Such investment strategy would suffer from a lower return and a higher volatility relative to the benchmark, so the overall performance is much lower than the performance of the hedged portfolio. If the decarbonised portfolio performed much worse than the benchmark in unhedged terms, it is because our portfolio rebalancing assigns stronger weights to European countries that issue sovereign securities in euro while the portfolio returns are expressed in dollar terms. During the rebalancing period, the dollar appreciated vis-a-vis the euro, thus suppressing returns from euro-denominated assets. The Sharpe ratio is equal to 1.1 and 0.6 for the hedged and unhedged portfolios, respectively. In addition, the tracking error is much higher for the unhedged strategy (1.6%against 1% for the hedged portfolio).

[Insert Table 3 here]

Given the excessive rebalancing implied by an ambitious target of carbon emissions reduction, we also consider setting a lower target of 5% per year, which would lead to an overall decrease by 22.6% over 5 years. Results are reported in Figure 3 with the dashed-dotted red line. The figure shows that in 2020 the carbon intensity of the NZ portfolio was reduced by 5%, with a substantial reduction in the tracking error and the active share. The reason is that due to the Covid crisis, the carbon intensity of the benchmark was reduced by 8.9% in that year, so that the 5% reduction could be attained at no cost.

As Table 3 also confirms, such a reduction in the GHG emissions financed by the portfolio can be obtained at no financial cost, as the Sharpe ratio increases and the tracking error volatility remains below 0.5% per year. It should be noted, however, that the decarbonised portfolio still requires a massive rebalancing between some countries. Among advanced economies, we will strongly overweigh Denmark, Spain and Sweden, and accordingly reduce the shares of Australia, Belgium, Canada, and the Netherlands. Among emerging economies, some countries, such as Colombia and the Philippines, are given a much larger share, whereas some other countries are virtually excluded from the portfolio, e.g., Malaysia, Poland, Russia, and Turkey.

Figure 4 allows us to visualise the evolution of the optimal weights for the 10% and 5% reduction targets for selected countries with large weights in the portfolio (Panel A for advanced economies and Panel B for emerging economies). This figure demonstrates that the 10% target can result in massive rebalancing, notably at the end of the sample, penalising Germany and the United States while favouring Italy and the United Kingdom). Among emerging economies, some large countries (Brazil, China, Mexico, Russia) are excluded from the optimal portfolio, while others (India, Indonesia) benefit from overweighting.

The figure also suggests that the composition of both advanced economies and emerging market segments are severely affected by the decarbonisation process. It is important to note that, as emerging countries have a limited weights in the benchmark, a large reallocation is necessary to reduce the overall emissions. With consumption-based emissions, Emerging economies have a low consumption-based carbon intensity and therefore can be massively overweighted (for instance, India and Philippines). With the production-based measure, the situation can be reverse and the same countries are massively underweighted or excluded. In the end, rebalancing Emerging markets contributes massively to the decarbonisation process for the 10% reduction target. In fact, overall, the GHG emission reduction is equal to 65.8% over the 5 years in Emerging markets and to 38.5% in Advanced economies. When, the target is equal to 5% per year, the contribution of Emerging market and Advanced economies are reduced to 38.6% and 20.1%, respectively.

[Insert Figure 4 here]

This first analysis illustrates three main points. First, a massive reduction in the GHG emissions financed by the portfolio can be massively reduced in a 5-year period, even if the benchmark itself is only marginally decarbonised (due to the overall limited reduction in GHG emissions by countries in the benchmark). Second, this reduction in GHG emissions is obtained at a limited financial cost. Third, the reduction in GHG emissions requires a massive rebalancing of the optimal portfolio, resulting in substantial over- and under-weighting of some large countries and therefore in a large active share.

Such massive reallocation would raise some concerns. First, it may be difficult for investors to accept too radical weight rebalancing, especially to exclude some countries completely from a diversified portfolio. This may be politically unfeasible or expose the portfolio to consequent currency risks. For instance, the baseline scenario with an objective of reducing carbon intensity by 10% a year would require investors to reduce their holdings of U.S. sovereign debt to 10% from 40% in 2019-20; this would probably be inconceivable for some institutional investors. Second, this rebalancing may entail macro-financial risks, for instance pushing up sovereign yields of countries whose debt is disinvested, and thus affect the average rating or the average duration of the portfolio.

## 3.3 The baseline analysis with weight constraints

To address the concerns raised above, we can impose some restrictions on country weight movement for portfolio optimisation. As an illustration, we consider the case where the weight of any country is capped from falling below 50% or surging to 150% relative to the benchmark weight.[5]

Results are reported in Figure 5. In comparison with the NZ portfolio in the unconstrained scenario (Figure 3), the target of 10% carbon intensity reduction per year over five years, ie a cumulative reduction of 41%, cannot be achieved due to weight constraints. The trajectory of the carbon intensity of the NZ portfolio in the constrained scenario (black line in Figure 5) is no longer a linear downward sloping line and cannot fall below 10 ton of CO2 per capita by 2020 as in Figure 3. The cumulative reduction over five years is only 30%, 11 percentage points lower than in the unconstrained case. However, if the target of carbon intensity reduction is reduced to 5% (red dash-dotted line), then portfolio rebalancing like in the unconstrained case can still be achieved, a cumulative reduction of 22.6%.

[Insert Figure 5 here]

As Table 4 demonstrates, the main difference between the constrained and unconstrained cases is that countries with high emissions per capita can no longer be excluded from the NZ portfolio because of the lower bound, whereas the weights of countries with low emissions cannot increase unlimitedly because of the higher bound. Therefore, the portfolio benefits more countries with intermediary levels of carbon intensity. For

[5] In this case, no country will be excluded from the decarbonised portfolio.

instance, Japan and Germany among advanced economies receive higher weights while those of Italy and the United Kingdom are reduced. Among emerging markets, the same reallocation of weights towards countries with intermediary level of carbon intensity is also observable, with China's weight increasing at the expenses of India.

Overall, for the NZ portfolio with an annual target of 10% carbon intensity reduction, the cumulative reduction is not reached after five years, but the changes in allocated weights and the tracking error relative to the benchmark (0.66% per year) are obviously smaller than in the reallocation without constraints. As Table 5 reveals, the financial performance is not affected.

[Insert Tables 4 and 5 here]

Restricting changes in portfolio weights limits the contribution of re-weighting across emerging markets issuers to the decarbonisation process. The reduction in carbon intensity in emerging market and advanced economies is equal to 17.1% and 28.6% with the 10% reduction target and to 16.5% and 21.1% with the 5% reduction target.

Optimal weights for the countries with high weights are reported in Figure 4 for advanced economies (Panel A) and emerging economies (Panel B). For most countries, the weight restrictions are binding at some point in the period (usually around 2018) even with the 5% reduction target.

[Insert Figure 6 here]

## 3.4 Alternative analysis

We have presented our baseline decarbonisation strategy using the consumption-based carbon intensity metric and the active share as the portfolio optimisation method. As discussed above, investors can use the production-based measure of carbon intensity, which will request emerging market economies to do more for carbon emission reduction. In Appendix A, we provide additional results based on the production-based approach to carbon intensity. As expected, reallocation is more radical for emerging economies than for advanced economies, because emerging economies' carbon intensity is much higher and exhibits large variation. Several emerging economies are totally excluded from the NZ portfolio in the unconstrained scenario, e.g., India and Indonesia. In contrast, some countries with low emissions per GDP receive much higher weights, such as Chile, Dominican Republic, Hungary, and Turkey. For advanced economies, we observe that some countries (Italy, Japan, Spain) are underweighed even if they received higher weights when the consumption-based carbon intensity measure was used. In addition, the United States is less penalised with the production-based intensity measure.

Appendix B presents additional results using tracking error for portfolio optimisation method. Compared with the baseline analysis, decarbonised portfolios achieve slightly lower returns but return volatilities have also reduced.

# 4 Policy implications and conclusion

In this paper, we present a strategy for investors to reduce carbon footprints of their sovereign securities portfolios. Using an *ad hoc* per capita metric of carbon emissions, we show that portfolio decarbonisation - reallocating funds from sovereign securities of high emitting countries to those of low emitting countries - can deliver a material reduction in a sovereign portfolio's overall carbon footprints.

Investors could have reduced the carbon intensity of a global sovereign portfolio by 41% between 2014 and 2019 (or 10% per year for five years in a row) with limited impact on the portfolio's financial performance. The bulk of this carbon intensity reduction could have been obtained by reducing the weight of the United States and consequently increasing the weights of France, Italy and Spain. To address investors' concerns about too big swings in sovereign issuers' weights in a portfolio, we also set upper and lower bounds for the changes in country weights and require the NZ portfolio to achieve the same credit rating as the BAU benchmark. This exercise under constraints limits the overall carbon intensity reduction that the NZ portfolio could achieve - a 30% cumulative reduction over five years instead of 41% - but still outperform the BAU benchmark. The strategy that we present in this paper is simple to implement and can be used by passive investors.

Important caveats should be borne in mind, however. First, we have considered that investors are price takers. If a significant share of investors would adopt this approach, there could be an impact on sovereign issuers' financing costs. In view of the sheer size of the Glasgow Net Zero Alliance portfolio, the implementation of our or other NZ investment strategies is bound to impact sovereigns' issuing conditions. We leave this analysis to follow-up research. Second, our analysis is based on countries' realised carbon reduction in the past and ignores sovereign issuers' forward-looking commitments. This penalises sovereign issuers whose efforts to reduce carbon emissions will only materialise in the medium term. It should be stressed, however, that any country that reduces more carbon emissions than others will be awarded in our NZ portfolio with an increasing share as soon as data on the country's carbon emission reduction become observable.

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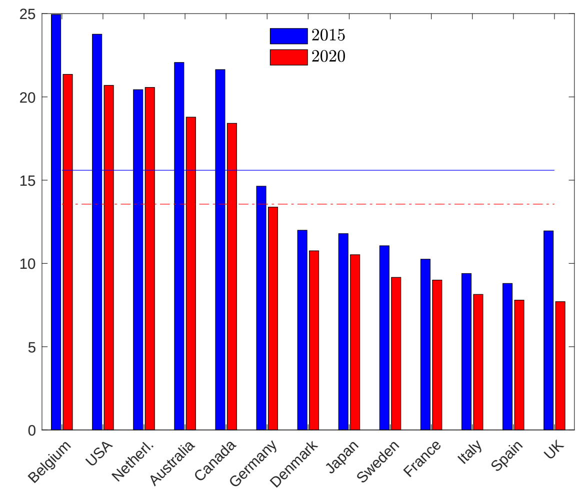
# 5 Figures

Figure 1: Carbon Intensity by Country

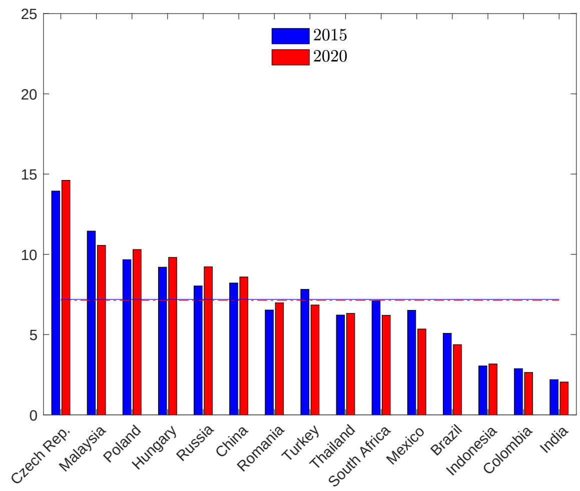
This figure displays the carbon intensity of the various countries under consideration for 2015 (in blue) and 2020 (in red). carbon intensity is the consumption-based measure in tons of $CO_2$ equivalent per capita in Panels A and B and the production-based measure in tons of $CO_2$ equivalent per million USD of GDP in Panels C and D. Countries are sorted by decreasing carbon intensity as of 2020. Blue and red horizontal lines corresponds to the average number in 2015 and 2020.

Panel A: Consumption per capita

Advanced Economies

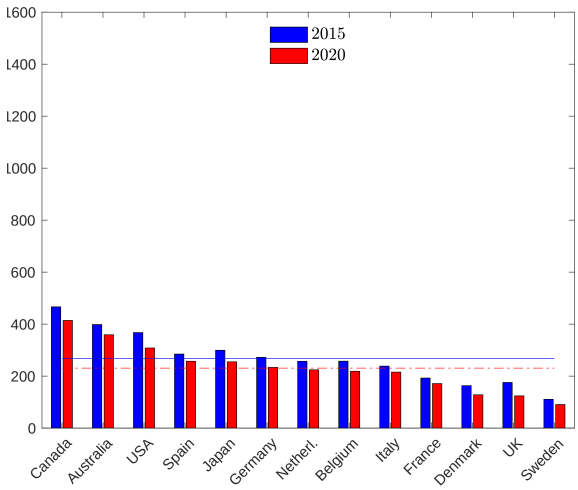



Emerging Markets Economies




Panel B: Production per GDP

Advanced Economies




Emerging Markets Economies

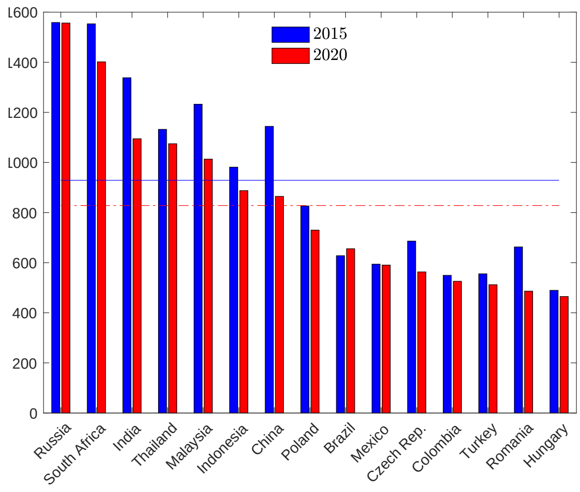


Figure 2: Scenarios based on carbon intensity metrics and performance tracking method

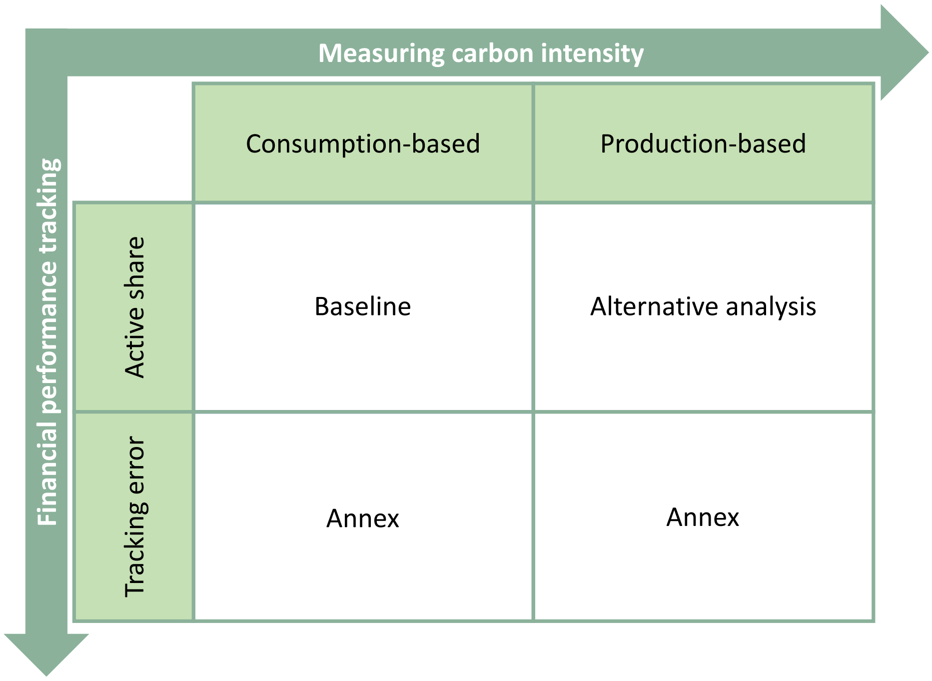
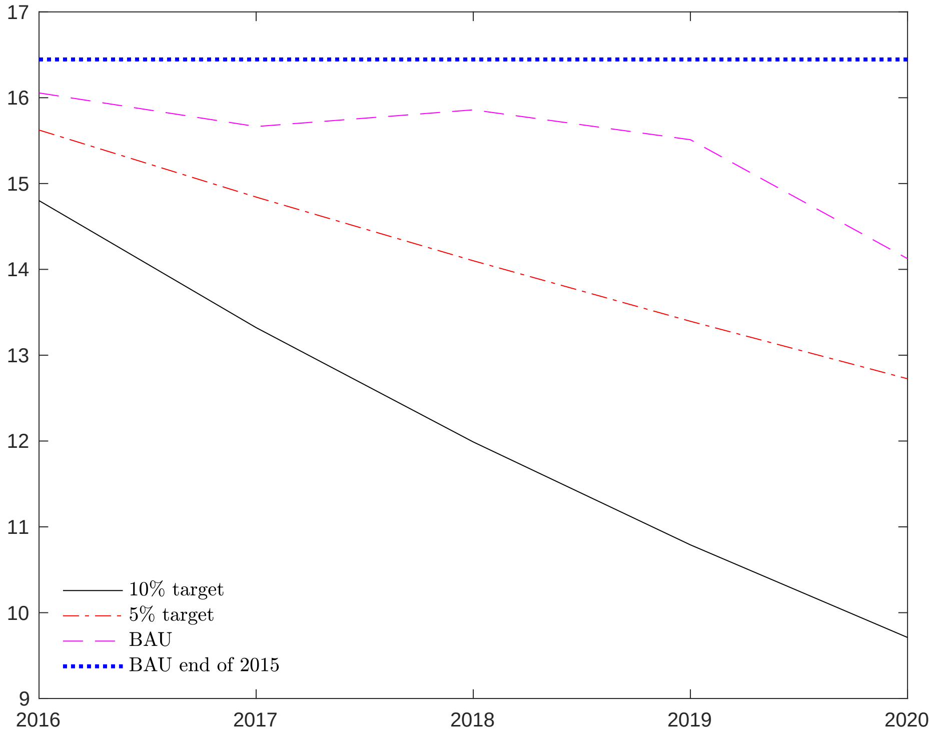


Figure 3: Minimisation of Active Share – Consumption per Capita

Panel A of this figure displays the consumption-based carbon emissions per capita of the various portfolios: the NZ portfolios with 10% (in black) and 5% (in red) reduction target and the BAU (in magenta). Panel B reports financial performance measures: the cumulative return relative to the BAU (monthly returns from 2017 to 2021), the active share, the annual tracking error, and the annual turnover.

Panel A: Consumption-based carbon emissions per capita




Panel B: Financial Performance

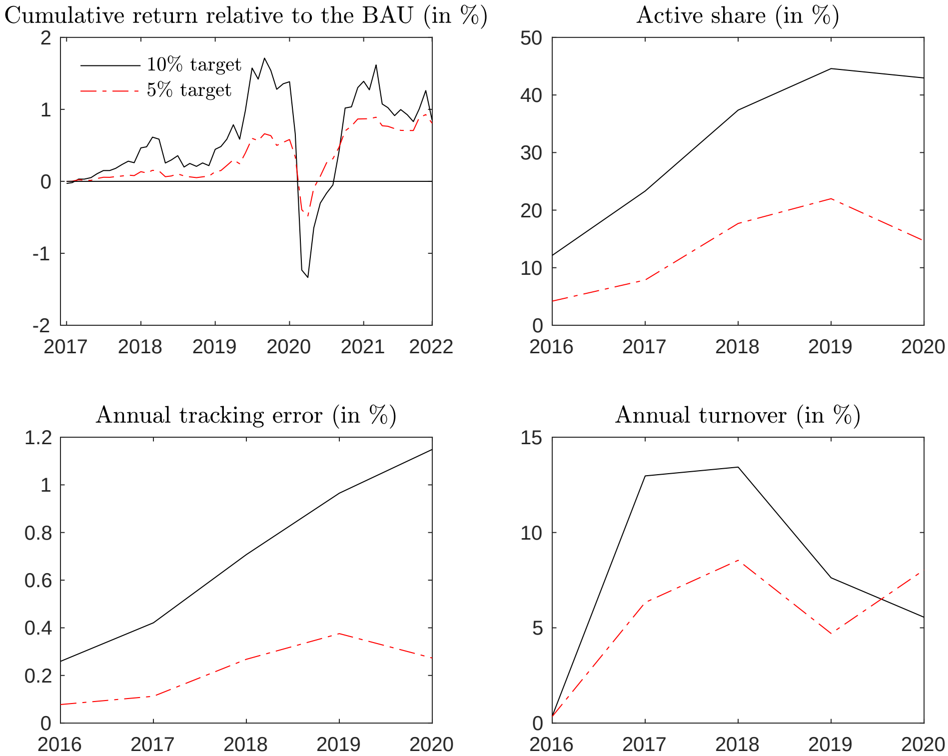
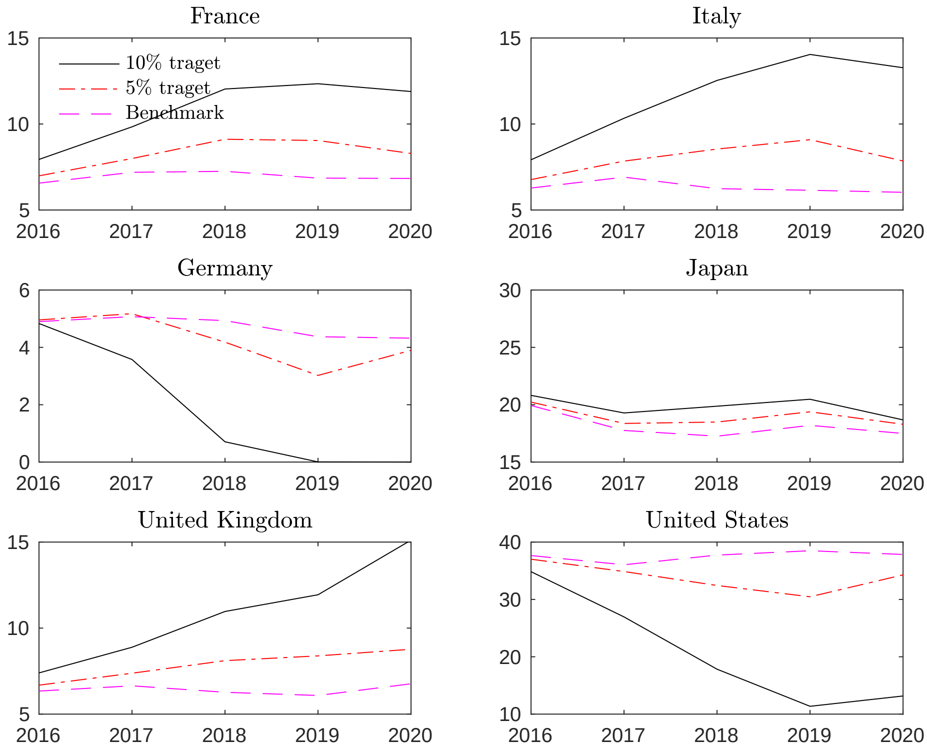


Figure 4: Optimal Weights – Consumption per Capita

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

Panel A: Advanced Economies




Panel B: Emerging Market Economies

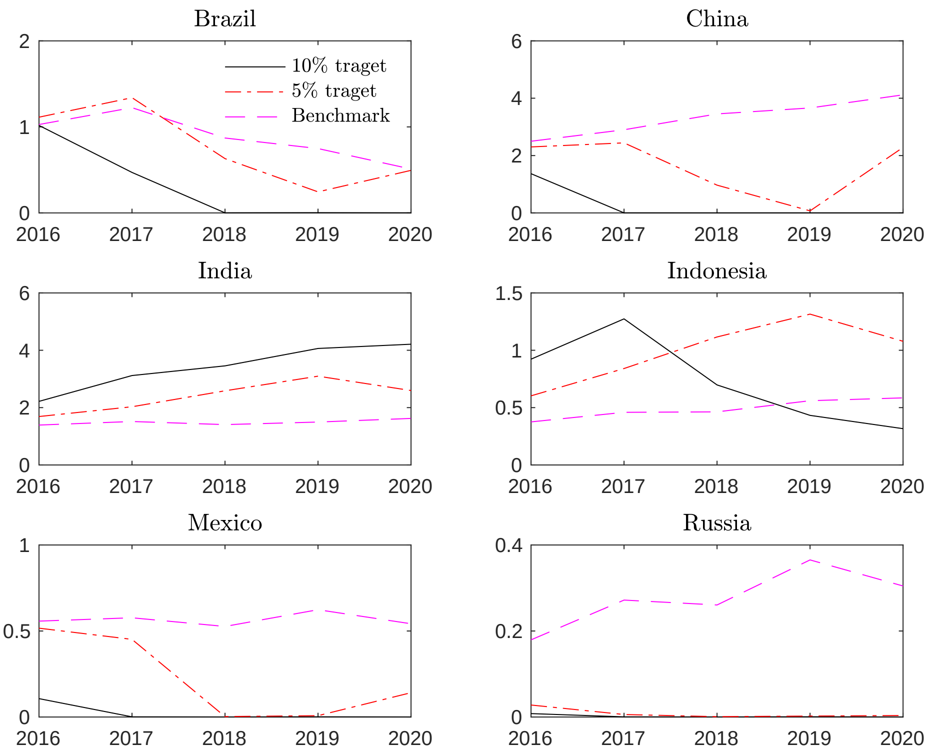
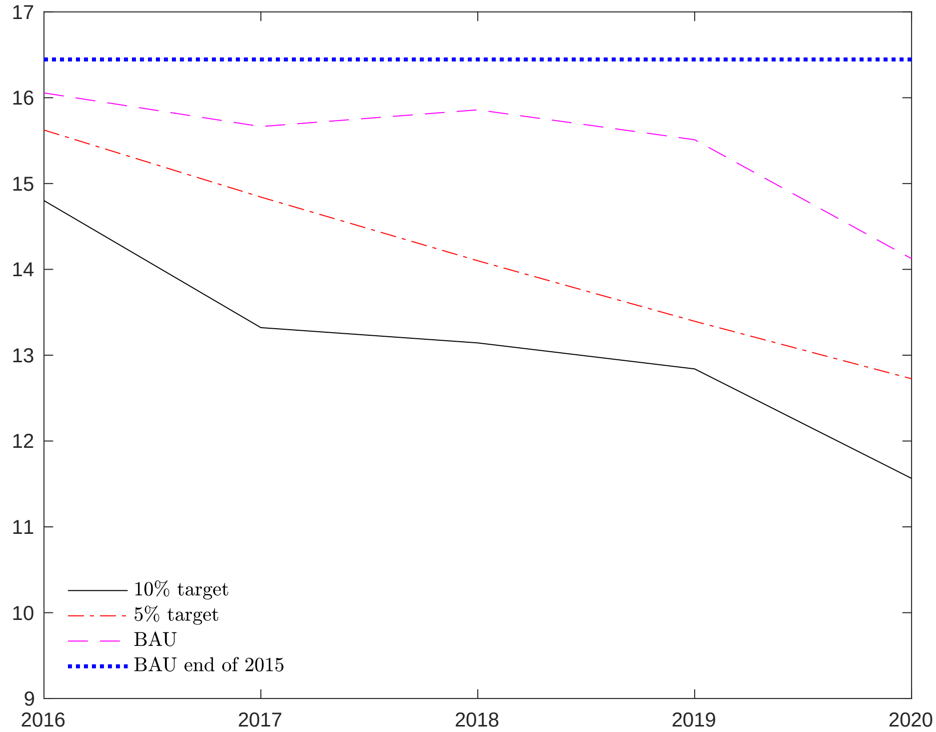


Figure 5: Minimisation of Active Share – Consumption per Capita with Constraints

Panel A of this figure displays the consumption-based carbon emissions per capita of the various portfolios: the NZ portfolios with 10% (in black) and 5% (in red) reduction target and the BAU (in magenta). Panel B reports financial performance measures: the cumulative return relative to the BAU (monthly returns from 2017 to 2021), the active share, the annual tracking error, and the annual turnover. The weights are capped from falling below 50% or surging to 150% relative to the benchmark weight.

Panel A: Consumption-based carbon emissions per capita




Panel B: Financial Performance

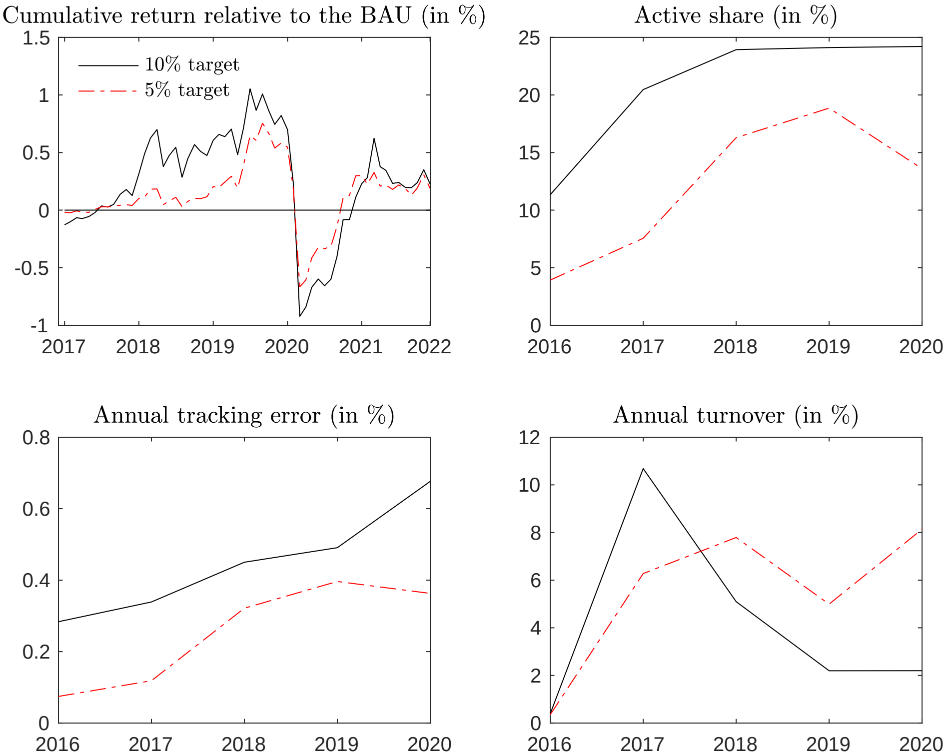
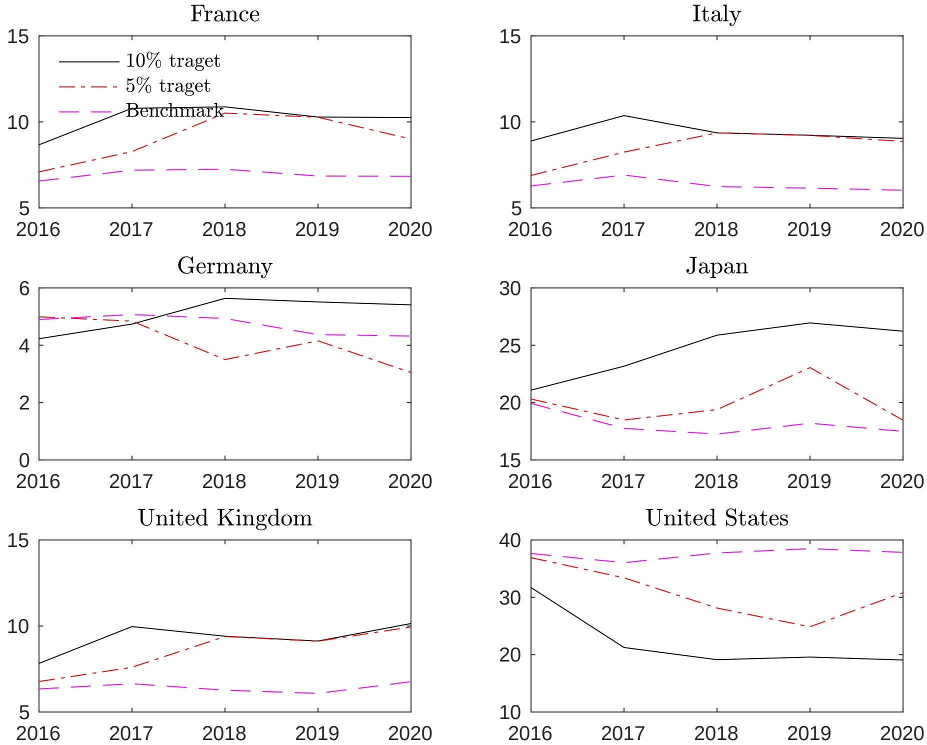


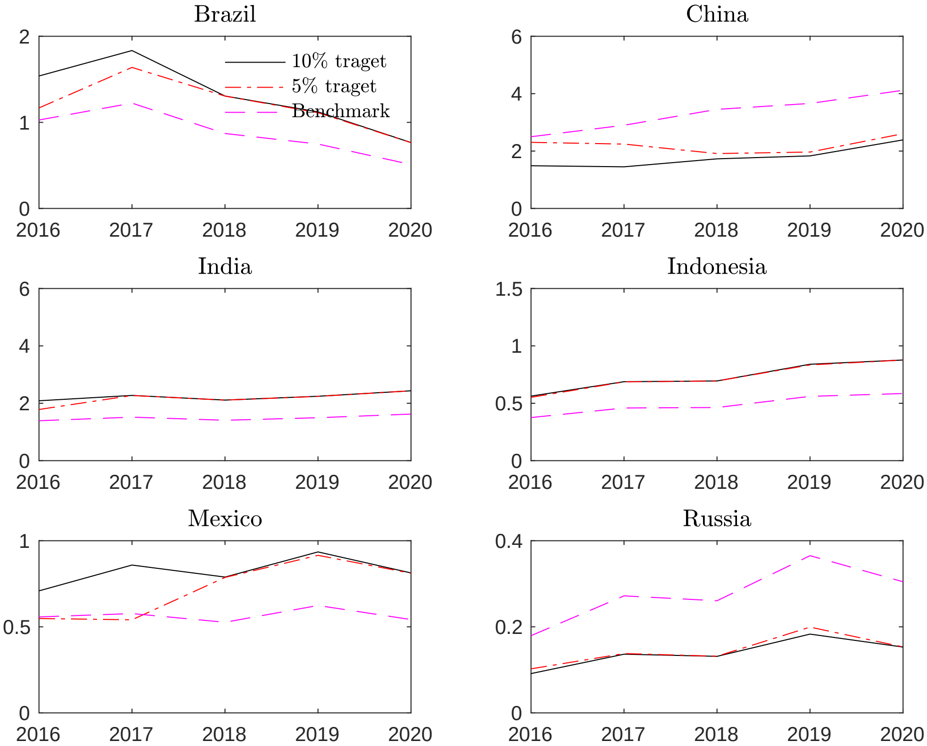
Figure 6: Optimal weights – Consumption per Capita – With Constraints

This figure displays the optimal weights of the various portfolios for a selection of countries: the NZ portfolios with 10% (in black) and 5% (in red) reduction target and the BAU (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 weight.

Panel A: Advanced Economies




Panel B: Emerging Market Economies



# 6 Tables

Table 1: Country Weight and Carbon Intensity

| Country | 2015 | | | | 2020 | | | |
|---|---|---|---|---|---|---|---|---|
| | Benchmark | | GHG emissions | | Benchmark | | Carbon 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 | 22.07 | 398.5 | 1.71 | 1.90 | 18.78 | 359.2 |
| Belgium | 1.69 | 1.81 | 24.95 | 257.6 | 1.64 | 1.82 | 21.35 | 218.7 |
| Canada | 1.16 | 1.25 | 21.64 | 466.7 | 1.55 | 1.72 | 18.41 | 414.3 |
| Denmark | 0.42 | 0.45 | 11.99 | 163.4 | 0.33 | 0.37 | 10.76 | 128.3 |
| France | 6.38 | 6.83 | 10.25 | 192.6 | 6.84 | 7.60 | 9.00 | 171.4 |
| Germany | 4.96 | 5.31 | 14.64 | 272.3 | 4.32 | 4.81 | 13.38 | 233.5 |
| Italy | 6.45 | 6.90 | 9.39 | 238.6 | 6.03 | 6.70 | 8.14 | 215.5 |
| Japan | 19.63 | 21.02 | 11.79 | 299.6 | 17.49 | 19.45 | 10.52 | 255.2 |
| Netherlands | 1.68 | 1.80 | 20.43 | 257.2 | 1.28 | 1.42 | 20.57 | 224.2 |
| Spain | 3.60 | 3.86 | 8.80 | 285.0 | 3.91 | 4.34 | 7.80 | 257.3 |
| Sweden | 0.33 | 0.35 | 11.06 | 110.9 | 0.23 | 0.25 | 9.16 | 90.8 |
| United Kingdom | 7.37 | 7.90 | 11.95 | 175.7 | 6.76 | 7.52 | 7.70 | 124.1 |
| United States | 38.49 | 41.23 | 23.76 | 367.6 | 37.84 | 42.08 | 20.69 | 308.3 |
| **Panel B: Emerging Economies** | | | | | | | | |
| Argentina | – | – | 5.90 | 574.8 | 0.00 | 0.01 | 5.08 | 585.8 |
| Brazil | 0.68 | 10.21 | 5.08 | 627.8 | 0.51 | 5.07 | 4.37 | 655.6 |
| Chile | 0.04 | 0.67 | 6.33 | 450.8 | 0.11 | 1.05 | 5.68 | 437.9 |
| China | 1.98 | 29.77 | 8.21 | 1144.1 | 4.12 | 40.87 | 8.59 | 864.7 |
| Colombia | 0.17 | 2.51 | 2.88 | 549.5 | 0.22 | 2.21 | 2.64 | 525.7 |
| Czech Rep. | – | – | 13.94 | 686.2 | 0.16 | 1.58 | 14.61 | 563.1 |
| Dominican Rep. | – | – | 3.08 | 418.8 | 0.01 | 0.06 | 2.89 | 345.3 |
| Hungary | 0.15 | 2.20 | 9.20 | 489.6 | 0.16 | 1.59 | 9.81 | 464.8 |
| India | 0.95 | 14.26 | 2.19 | 1338.1 | 1.62 | 16.11 | 2.04 | 1094.6 |
| Indonesia | 0.26 | 3.95 | 3.05 | 981.4 | 0.58 | 5.81 | 3.17 | 887.5 |
| Malaysia | 0.27 | 4.06 | 11.45 | 1232.6 | 0.28 | 2.78 | 10.56 | 1013.5 |
| Mexico | 0.70 | 10.60 | 6.51 | 594.0 | 0.54 | 5.38 | 5.35 | 590.4 |
| Peru | 0.05 | 0.72 | 3.05 | 579.0 | 0.12 | 1.14 | 2.73 | 538.6 |
| Philippines | 0.01 | 0.20 | 1.79 | 669.9 | 0.01 | 0.07 | 1.94 | 622.1 |
| Poland | 0.33 | 4.94 | 9.67 | 826.4 | 0.34 | 3.40 | 10.30 | 730.0 |
| Romania | 0.08 | 1.20 | 6.53 | 662.9 | 0.13 | 1.26 | 6.98 | 486.2 |
| Russia | 0.15 | 2.24 | 8.03 | 1558.8 | 0.30 | 3.02 | 9.22 | 1556.7 |
| South Africa | 0.30 | 4.59 | 7.12 | 1553.3 | 0.40 | 3.93 | 6.20 | 1401.6 |
| Thailand | 0.24 | 3.56 | 6.22 | 1132.2 | 0.38 | 3.79 | 6.32 | 1074.6 |
| Turkey | 0.29 | 4.34 | 7.82 | 555.6 | 0.08 | 0.82 | 6.84 | 512.1 |
| Uruguay | – | – | 8.49 | 687.0 | 0.01 | 0.05 | 7.65 | 628.8 |

Note: This table reports the number of firms in the Trucost dataset; the number of firms in the MSCI ACWI and its two main components (Developed markets and Emerging markets); the proportion of firms covered by the index with carbon measures in Trucost; and the proportion of the market capitalization of the index with carbon measures in Trucost. The sample covers the period from 2005 to 2019.

Table 2: Minimisation of the Active Share: Optimal Weights

| | BAU portfolio | NZ portfolio 10% reduction | NZ portfolio 5% reduction |
|---|---|---|---|
| **Panel A: Advanced economies** | 90.61 | 90.61 | 90.61 |
| Australia | 1.49 | 0.00 | 0.27 |
| Belgium | 1.71 | 0.00 | 0.23 |
| Canada | 1.29 | 0.00 | 0.24 |
| Denmark | 0.39 | 1.44 | 1.06 |
| France | 6.94 | 10.81 | 8.28 |
| Germany | 4.72 | 1.82 | 4.25 |
| Italy | 6.32 | 11.62 | 8.02 |
| Japan | 18.13 | 19.83 | 18.95 |
| Netherlands | 1.45 | 0.01 | 0.38 |
| Spain | 3.93 | 9.73 | 5.74 |
| Sweden | 0.27 | 3.67 | 1.51 |
| United Kingdom | 6.42 | 10.86 | 7.87 |
| United States of America | 37.55 | 20.83 | 33.81 |
| **Panel B: Emerging economies** | 9.39 | 9.39 | 9.39 |
| Argentina | 0.02 | 0.00 | 0.02 |
| Brazil | 0.87 | 0.29 | 0.74 |
| Chile | 0.09 | 0.00 | 0.02 |
| China | 3.31 | 0.27 | 1.56 |
| Colombia | 0.23 | 1.29 | 0.91 |
| Czech Republic | 0.14 | 0.00 | 0.00 |
| Dominican Republic | 0.01 | 0.35 | 0.71 |
| Hungary | 0.16 | 0.00 | 0.00 |
| India | 1.48 | 3.36 | 2.33 |
| Indonesia | 0.49 | 0.72 | 0.96 |
| Malaysia | 0.23 | 0.00 | 0.00 |
| Mexico | 0.56 | 0.02 | 0.22 |
| Peru | 0.10 | 0.85 | 0.70 |
| Philippines | 0.01 | 2.21 | 0.97 |
| Poland | 0.39 | 0.00 | 0.02 |
| Romania | 0.11 | 0.00 | 0.02 |
| Russian Federation | 0.28 | 0.00 | 0.01 |
| South Africa | 0.39 | 0.00 | 0.09 |
| Thailand | 0.33 | 0.01 | 0.08 |
| Turkey | 0.19 | 0.00 | 0.03 |
| Uruguay | 0.01 | 0.00 | 0.00 |

Note: This table reports the average weight of each country in the BAU portfolio and the NZ portfolios with 10% and 5% reduction targets.

Table 3: Minimisation of the Active Share: Financial Performance

| | BAU portfolio | NZ portfolio 10% reduction | NZ portfolio 5% reduction |
|---|---|---|---|
| **Panel A: General performance** | | | |
| Annual active share | – | 32.1% | 13.3% |
| Annual turnover | 0.0% | 9.9% | 6.9% |
| Average rating | 17.19 | 16.27 | 16.83 |
| Reduction in carbon intensity | -14.1% | -41.0% | -22.6% |
| Reduction in GHG emissions | -4.3% | -58.9% | -15.7% |
| **Panel B: Performance of hedged portfolio** | | | |
| Annual return | 3.19% | 3.33% | 3.32% |
| Annual volatility | 3.03% | 3.14% | 3.03% |
| Ex post Sharpe Ratio | 1.05 | 1.06 | 1.10 |
| Annual tracking error | – | 1.04% | 0.41% |
| **Panel C: Performance of unhedged portfolio** | | | |
| Annual return | 3.11% | 3.05% | 3.20% |
| Annual volatility | 4.27% | 5.14% | 4.49% |
| Ex post Sharpe Ratio | 0.73 | 0.59 | 0.71 |
| Annual tracking error | – | 1.56% | 0.50% |

Note: Panel A of this table reports some characteristics of the BAU portfolio and the NZ portfolios with 10% and 5% reduction targets, the average annual share, the annual turnover the average rating, the reduction in carbon intensity and in GHG 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.

Table 4: Minimisation of the Active Share: Optimal Weights with Constraints

| | BAU portfolio | NZ portfolio 10% reduction | NZ portfolio 5% reduction |
|---|---|---|---|
| **Panel A: Advanced economies** | 90.61 | 90.61 | 90.61 |
| Australia | 1.49 | 0.75 | 0.77 |
| Belgium | 1.71 | 0.86 | 0.86 |
| Canada | 1.29 | 0.65 | 0.67 |
| Denmark | 0.39 | 0.59 | 0.58 |
| France | 6.94 | 10.17 | 9.03 |
| Germany | 4.72 | 5.10 | 4.11 |
| Italy | 6.32 | 9.38 | 8.51 |
| Japan | 18.13 | 24.66 | 19.94 |
| Netherlands | 1.45 | 0.72 | 0.79 |
| Spain | 3.93 | 5.89 | 5.55 |
| Sweden | 0.27 | 0.41 | 0.41 |
| United Kingdom | 6.42 | 9.29 | 8.56 |
| United States of America | 37.55 | 22.15 | 30.83 |
| **Panel B: Emerging economies** | 9.39 | 9.39 | 9.39 |
| Argentina | 0.02 | 0.02 | 0.02 |
| Brazil | 0.87 | 1.31 | 1.19 |
| Chile | 0.09 | 0.13 | 0.12 |
| China | 3.31 | 1.77 | 2.20 |
| Colombia | 0.23 | 0.35 | 0.34 |
| Czech Republic | 0.14 | 0.07 | 0.07 |
| Dominican Republic | 0.01 | 0.01 | 0.01 |
| Hungary | 0.16 | 0.08 | 0.08 |
| India | 1.48 | 2.22 | 2.16 |
| Indonesia | 0.49 | 0.73 | 0.73 |
| Malaysia | 0.23 | 0.12 | 0.12 |
| Mexico | 0.56 | 0.82 | 0.72 |
| Peru | 0.10 | 0.15 | 0.15 |
| Philippines | 0.01 | 0.01 | 0.01 |
| Poland | 0.39 | 0.20 | 0.20 |
| Romania | 0.11 | 0.13 | 0.08 |
| Russian Federation | 0.28 | 0.14 | 0.14 |
| South Africa | 0.39 | 0.48 | 0.47 |
| Thailand | 0.33 | 0.49 | 0.43 |
| Turkey | 0.19 | 0.16 | 0.13 |
| Uruguay | 0.01 | 0.01 | 0.01 |

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

Table 5: Minimisation of the Active Share: Financial Performance with Constraints

| | BAU portfolio | NZ portfolio 10% reduction | 5% reduction |
|---|---|---|---|
| **Panel A: General performance** | | | |
| Annual active share | – | 20.8% | 12.0% |
| Annual turnover | 0.0% | 5.0% | 6.8% |
| Average rating | 17.19 | 16.51 | 16.77 |
| Reduction in carbon intensity | -14.1% | -29.7% | -22.6% |
| Reduction in GHG emissions | -4.3% | -38.8% | -20.3% |
| **Panel B: Performance of hedged portfolio** | | | |
| Annual return | 3.19% | 3.22% | 3.22% |
| Annual volatility | 3.03% | 2.97% | 3.05% |
| Ex post Sharpe Ratio | 1.05 | 1.09 | 1.06 |
| Annual tracking error | – | 0.66% | 0.45% |
| **Panel C: Performance of unhedged portfolio** | | | |
| Annual return | 3.11% | 2.87% | 3.11% |
| Annual volatility | 4.27% | 4.92% | 4.60% |
| Ex post Sharpe Ratio | 0.73 | 0.58 | 0.68 |
| Annual tracking error | – | 1.06% | 0.70% |

Note: Panel A of this table reports some characteristics of the BAU portfolio and the NZ portfolios with 10% and 5% reduction targets, the average annual share, the annual turnover the average rating, the reduction in carbon intensity and in GHG 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.

# Appendices

## A Production-based Measure of GHG Emissions

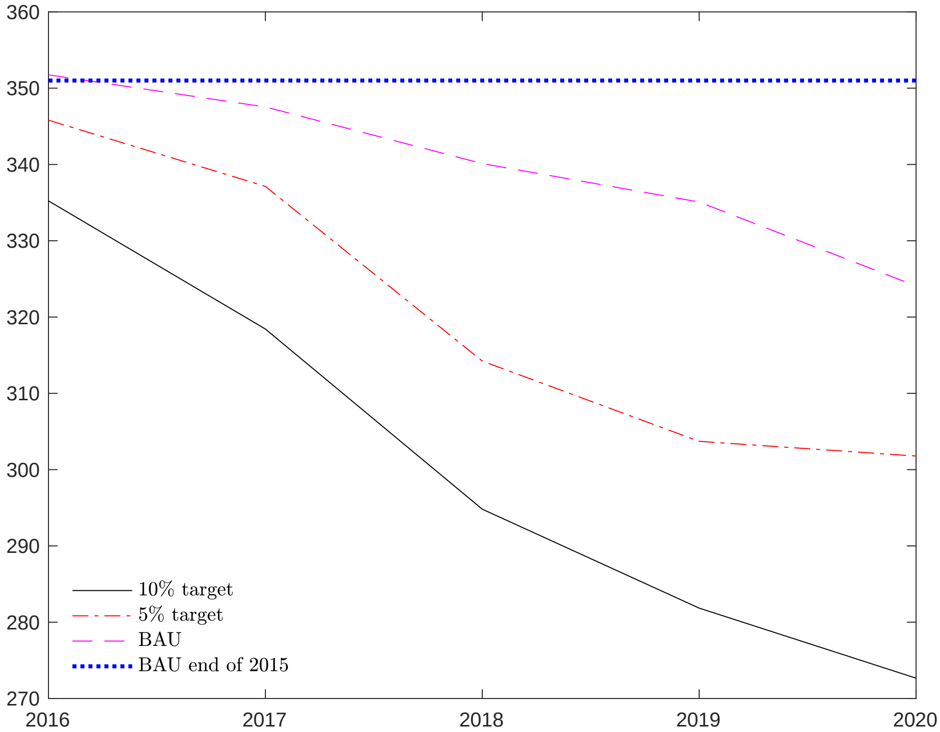
Figure A.2 reproduces the same set of results with the production-based carbon intensity metric. In both cases, the decarbonised portfolio's carbon intensity is reduced by 41% between 2015 and 2020, which corresponds to a 10% decrease per year each year. We notice that, for both measures of carbon intensity, the benchmark portfolio's carbon intensity is also reducing due to countries' natural effort in reducing carbon missions, but the magnitude is much smaller, i.e., by 14.1% using the consumption-based measure and 7.7% using the production-based measure. The bottom two graphs on our performance tracking metrics clearly the increasing cost associated with portfolio decarbonisation for investors in terms of the distance to the benchmark. The annual tracking error reached 1.15% and the active share 43% in 2020.

Regarding the financial performance of the optimal portfolio (Table A.2), we note that the Sharpe ratio is lower but the tracking error also is lower than with the consumption-based measure. Interestingly, Figure A.2 illustrates that the tracking error and the active share increase in 2020, even with the 5% emissions reduction target. The reason is that the emissions of the benchmark only marginally decrease during the Covid crisis (by 3.9%) when measured by the production-based carbon intensity.

## Figure A.1: Minimisation of Active Share – Production per GDP

Panel A of this figure displays the production-based carbon emissions per GDP of the various portfolios: the NZ portfolios with 10% (in black) and 5% (in red) reduction target and the BAU (in magenta). Panel B reports financial performance measures: the cumulative return relative to the BAU (monthly returns from 2017 to 2021), the active share, the annual tracking error, and the annual turnover.

### Panel A: Production-based carbon emissions per GDP




### Panel B: Financial Performance

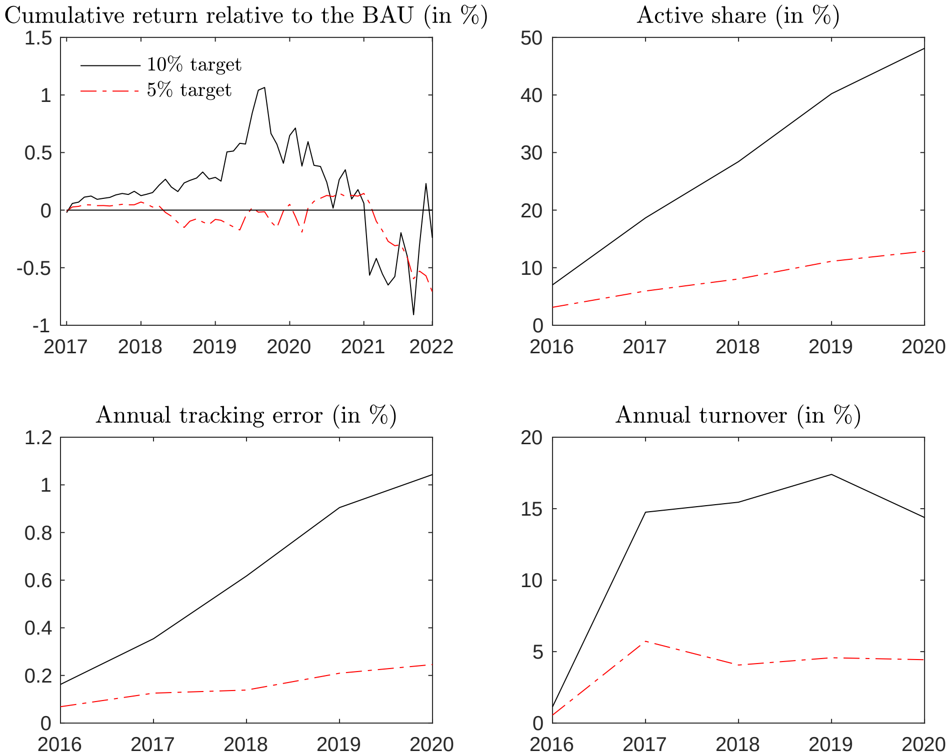
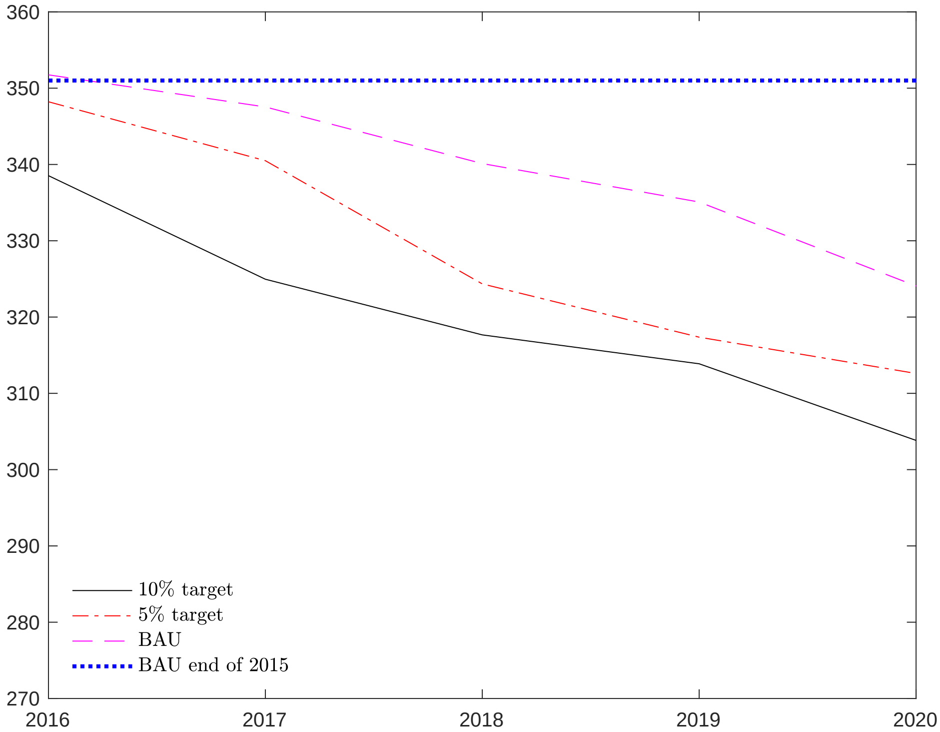


Figure A.2: Minimisation of Active Share – Production per GDP with Constraints

Panel A of this figure displays the production-based carbon emissions per GDP of the various portfolios: the NZ portfolios with 10% (in black) and 5% (in red) reduction target and the BAU (in magenta). Panel B reports financial performance measures: the cumulative return relative to the BAU (monthly returns from 2017 to 2021), the active share, the annual tracking error, and the annual turnover. The weights are capped from falling below 50% or surging to 150% relative to the benchmark weight.

Panel A: Production-based carbon emissions per GDP




Panel B: Financial Performance

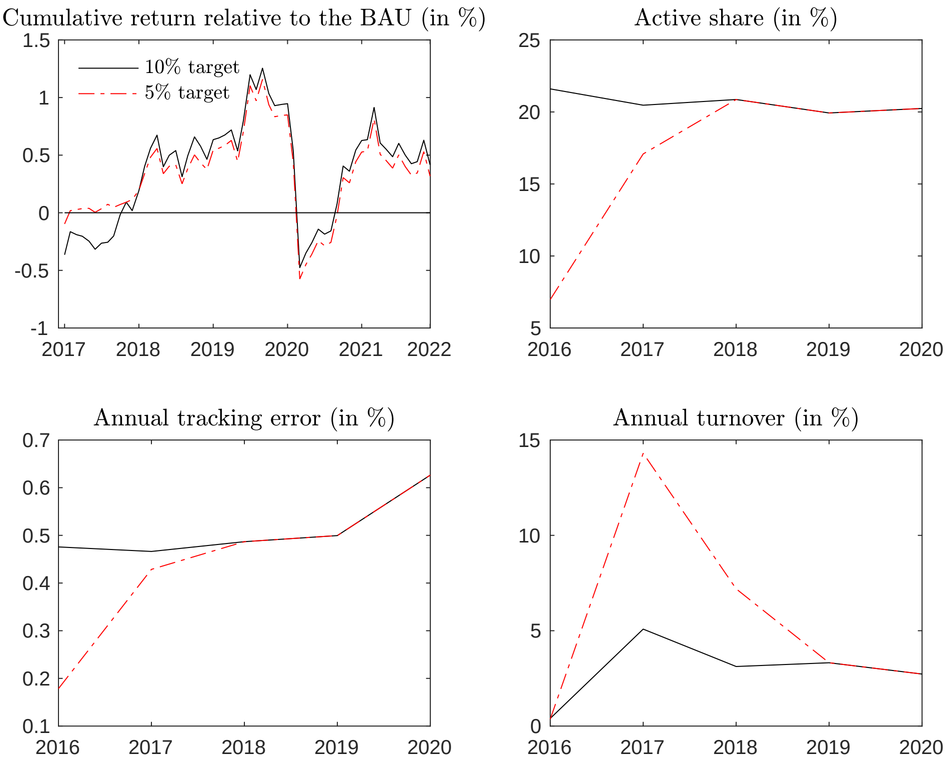


Table A.1: Minimisation of the Active Share: Optimal Weights

| | BAU portfolio | NZ portfolio 10% reduction | NZ portfolio 5% reduction |
|---|---|---|---|
| **Panel A: Advanced economies** | 90.61 | 90.61 | 90.61 |
| Australia | 1.49 | 0.15 | 0.65 |
| Belgium | 1.71 | 0.81 | 1.76 |
| Canada | 1.29 | 0.07 | 0.36 |
| Denmark | 0.39 | 5.30 | 1.00 |
| France | 6.94 | 9.19 | 7.30 |
| Germany | 4.72 | 2.66 | 4.68 |
| Italy | 6.32 | 5.75 | 6.42 |
| Japan | 18.13 | 14.58 | 17.95 |
| Netherlands | 1.45 | 0.70 | 1.48 |
| Spain | 3.93 | 1.58 | 3.77 |
| Sweden | 0.27 | 7.98 | 1.15 |
| United Kingdom | 6.42 | 11.49 | 7.04 |
| United States of America | 37.55 | 30.36 | 37.03 |
| **Panel B: Emerging economies** | 9.39 | 9.39 | 9.39 |
| Argentina | 0.02 | 0.00 | 0.18 |
| Brazil | 0.87 | 0.19 | 0.67 |
| Chile | 0.09 | 1.24 | 1.04 |
| China | 3.31 | 0.10 | 1.25 |
| Colombia | 0.23 | 0.26 | 0.63 |
| Czech Republic | 0.14 | 0.00 | 0.23 |
| Dominican Republic | 0.01 | 6.27 | 1.89 |
| Hungary | 0.16 | 0.65 | 0.92 |
| India | 1.48 | 0.00 | 0.13 |
| Indonesia | 0.49 | 0.00 | 0.03 |
| Malaysia | 0.23 | 0.00 | 0.00 |
| Mexico | 0.56 | 0.14 | 0.59 |
| Peru | 0.10 | 0.20 | 0.46 |
| Philippines | 0.01 | 0.03 | 0.07 |
| Poland | 0.39 | 0.00 | 0.07 |
| Romania | 0.11 | 0.07 | 0.59 |
| Russian Federation | 0.28 | 0.00 | 0.00 |
| South Africa | 0.39 | 0.00 | 0.00 |
| Thailand | 0.33 | 0.00 | 0.00 |
| Turkey | 0.19 | 0.23 | 0.59 |
| Uruguay | 0.01 | 0.00 | 0.03 |

Note: This table reports the average weight of each country in the BAU portfolio and the NZ portfolios with 10% and 5% reduction targets.

Table A.2: Minimisation of the Active Share: Financial Performance

| | BAU portfolio | NZ portfolio 10% reduction | NZ portfolio 5% reduction |
|---|---|---|---|
| **Panel A: General performance** | | | |
| Annual active share | – | 28.5% | 8.2% |
| Annual turnover | 0.0% | 15.5% | 4.7% |
| Average rating | 17.19 | 17.20 | 17.08 |
| Reduction in carbon intensity | -14.1% | -41.0% | -22.6% |
| Reduction in GHG emissions | -4.3% | -50.3% | -20.8% |
| **Panel B: Performance of hedged portfolio** | | | |
| Annual return | 3.19% | 3.16% | 3.06% |
| Annual volatility | 3.03% | 3.41% | 3.08% |
| Ex post Sharpe Ratio | 1.05 | 0.93 | 0.99 |
| Annual tracking error | – | 0.63% | 0.21% |
| **Panel C: Performance of unhedged portfolio** | | | |
| Annual return | 3.11% | 2.78% | 2.63% |
| Annual volatility | 4.27% | 4.92% | 4.51% |
| Ex post Sharpe Ratio | 0.73 | 0.57 | 0.58 |
| Annual tracking error | – | 1.11% | 0.47% |

Note: Panel A of this table reports some characteristics of the BAU portfolio and the NZ portfolios with 10% and 5% reduction targets, the average annual share, the annual turnover the average rating, the reduction in carbon intensity and in GHG 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.

Table A.3: Minimisation of the Active Share: Optimal Weights with Constraints

| | BAU portfolio | NZ portfolio 10% reduction | NZ portfolio 5% reduction |
|---|---|---|---|
| **Panel A: Advanced economies** | 90.61 | 90.61 | 90.61 |
| Australia | 1.49 | 0.75 | 0.75 |
| Belgium | 1.71 | 2.57 | 2.43 |
| Canada | 1.29 | 0.65 | 0.65 |
| Denmark | 0.39 | 0.59 | 0.59 |
| France | 6.94 | 10.41 | 10.10 |
| Germany | 4.72 | 7.08 | 6.48 |
| Italy | 6.32 | 9.48 | 8.97 |
| Japan | 18.13 | 20.95 | 19.27 |
| Netherlands | 1.45 | 2.17 | 2.03 |
| Spain | 3.93 | 5.88 | 5.13 |
| Sweden | 0.27 | 0.41 | 0.41 |
| United Kingdom | 6.42 | 9.63 | 9.48 |
| United States of America | 37.55 | 20.05 | 24.32 |
| **Panel B: Emerging economies** | 9.39 | 9.39 | 9.39 |
| Argentina | 0.02 | 0.02 | 0.02 |
| Brazil | 0.87 | 1.31 | 1.31 |
| Chile | 0.09 | 0.13 | 0.13 |
| China | 3.31 | 3.11 | 3.11 |
| Colombia | 0.23 | 0.34 | 0.34 |
| Czech Republic | 0.14 | 0.21 | 0.21 |
| Dominican Republic | 0.01 | 0.01 | 0.01 |
| Hungary | 0.16 | 0.24 | 0.24 |
| India | 1.48 | 0.74 | 0.74 |
| Indonesia | 0.49 | 0.61 | 0.61 |
| Malaysia | 0.23 | 0.12 | 0.12 |
| Mexico | 0.56 | 0.84 | 0.84 |
| Peru | 0.10 | 0.15 | 0.15 |
| Philippines | 0.01 | 0.01 | 0.01 |
| Poland | 0.39 | 0.58 | 0.58 |
| Romania | 0.11 | 0.16 | 0.16 |
| Russian Federation | 0.28 | 0.14 | 0.14 |
| South Africa | 0.39 | 0.19 | 0.19 |
| Thailand | 0.33 | 0.16 | 0.16 |
| Turkey | 0.19 | 0.29 | 0.29 |
| Uruguay | 0.01 | 0.01 | 0.01 |

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

Table A.4: Minimisation of the Active Share: Financial Performance with Constraints

| | BAU portfolio | NZ portfolio 10% reduction | NZ portfolio 5% reduction |
|---|---|---|---|
| **Panel A: General performance** | | | |
| Annual active share | – | 20.6% | 17.0% |
| Annual turnover | 0.0% | 3.6% | 6.9% |
| Average rating | 17.19 | 16.71 | 16.85 |
| Reduction in carbon intensity | -14.1% | -15.9% | -15.9% |
| Reduction in GHG emissions | -4.3% | -30.0% | -30.0% |
| **Panel B: Performance of hedged portfolio** | | | |
| Annual return | 3.19% | 3.26% | 3.24% |
| Annual volatility | 3.03% | 3.07% | 3.06% |
| Ex post Sharpe Ratio | 1.05 | 1.06 | 1.06 |
| Annual tracking error | – | 0.66% | 0.60% |
| **Panel C: Performance of unhedged portfolio** | | | |
| Annual return | 3.11% | 3.09% | 2.83% |
| Annual volatility | 4.27% | 5.03% | 4.88% |
| Ex post Sharpe Ratio | 0.73 | 0.62 | 0.58 |
| Annual tracking error | – | 1.21% | 1.08% |

Note: Panel A of this table reports some characteristics of the BAU portfolio and the NZ portfolios with 10% and 5% reduction targets, the average annual share, the annual turnover the average rating, the reduction in carbon intensity and in GHG 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.

# B Optimisation Based on the Tracking Error

In the second experiment, we minimise the tracking error of the portfolio with respect to the benchmark. The tracking error relies on the covariance matrix of returns, which may be estimated with large uncertainty.

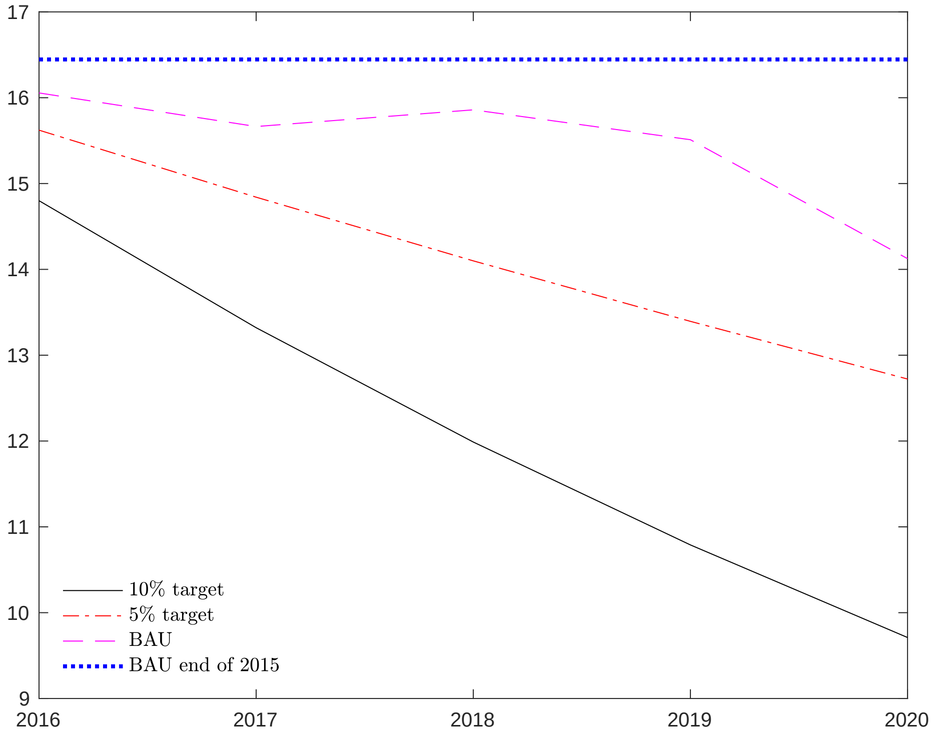
Results are reported in Figure A.3 for the consumption-based measure of GHG emissions and for the 10% (Panel A) and 5% (Panel B) reduction targets. Table A.5 reports the weights of the benchmark and optimal portfolios. Table A.6 reports the financial performance of the benchmark and optimal portfolios.

Results are reported in Figure A.4 for the consumption-based measure of GHG emissions with constraints on weights. Table A.7 reports the weights of the benchmark and optimal portfolios. Table A.8 reports the financial performance of the benchmark and optimal portfolios.

Figure A.3: Minimisation of Tracking Error – Consumption per Capita

Panel A of this figure displays the consumption-based carbon emissions per capita of the various portfolios: the NZ portfolios with 10% (in black) and 5% (in red) reduction target and the BAU (in magenta). Panel B reports financial performance measures: the cumulative return relative to the BAU (monthly returns from 2017 to 2021), the active share, the annual tracking error, and the annual turnover.

Panel A: Consumption-based carbon emissions per capita




Panel B: Financial Performance

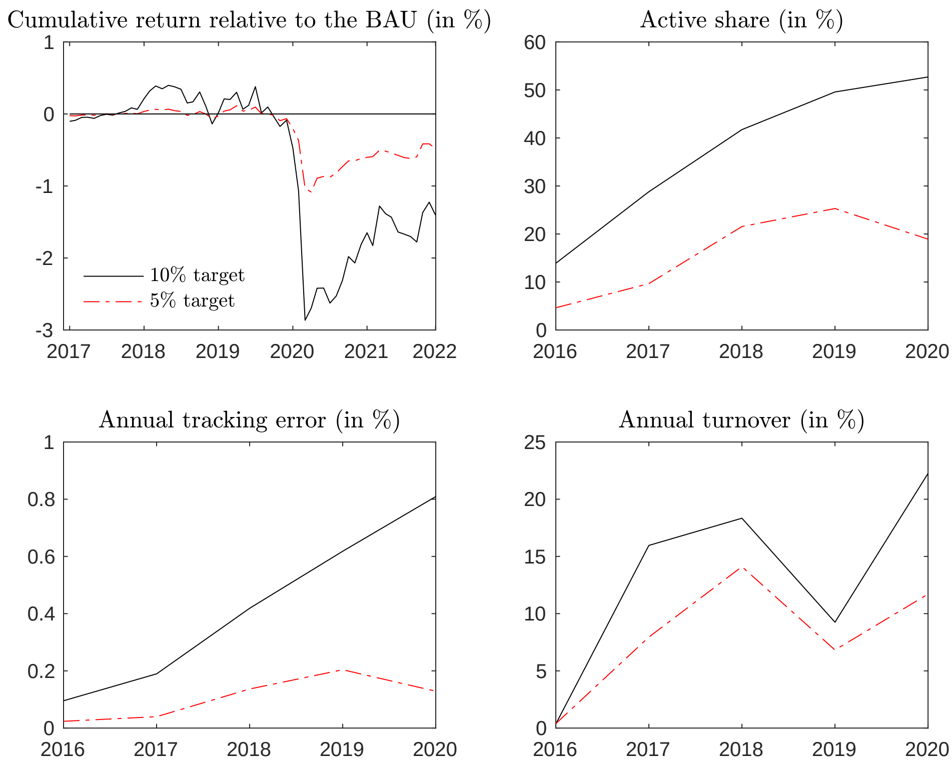
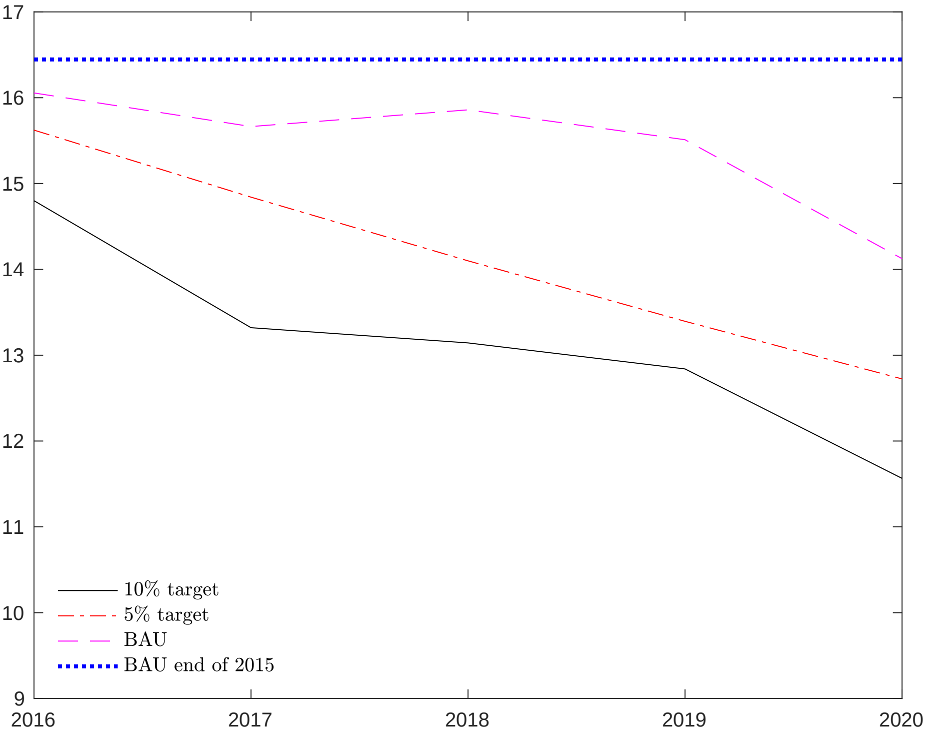


Figure A.4: Minimisation of Tracking Error – Consumption per Capita with Constraints

Panel A of this figure displays the consumption-based carbon emissions per capita of the various portfolios: the NZ portfolios with 10% (in black) and 5% (in red) reduction target and the BAU (in magenta). Panel B reports financial performance measures: the cumulative return relative to the BAU (monthly returns from 2017 to 2021), the active share, the annual tracking error, and the annual turnover. The weights are capped from falling below 50% or surging to 150% relative to the benchmark weight.

Panel A: Consumption-based carbon emissions per capita




Panel B: Financial Performance

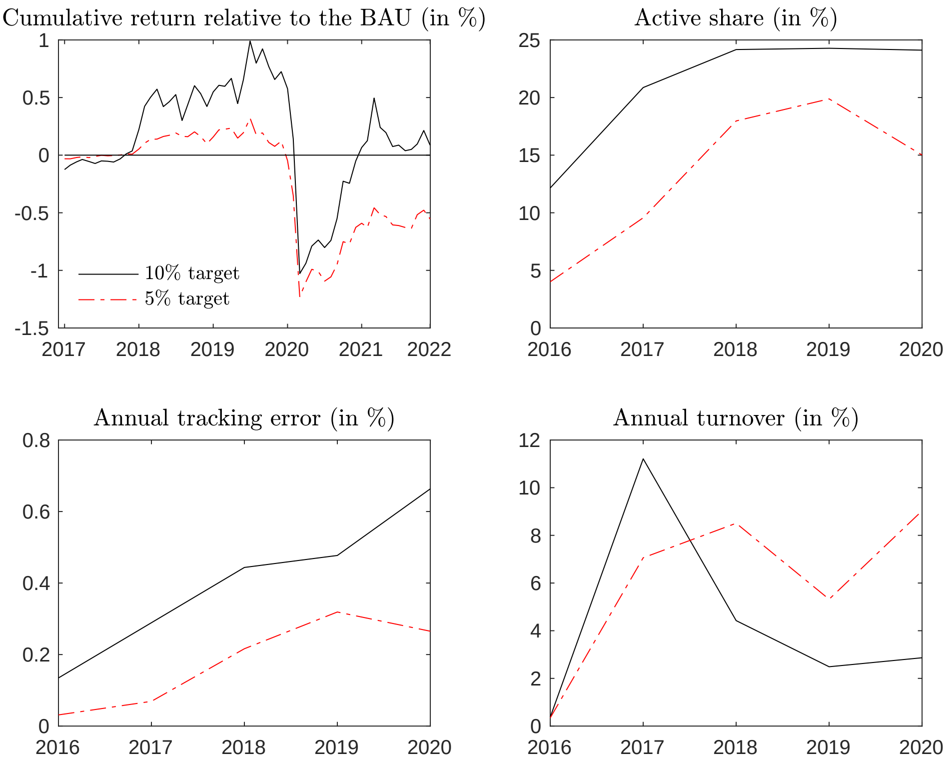


Table A.5: Minimisation of the Tracking Error: Optimal Weights

| | BAU portfolio | NZ portfolio 10% reduction | NZ portfolio 5% reduction |
|---|---|---|---|
| **Panel A: Advanced economies** | 90.61 | 90.61 | 90.61 |
| Australia | 1.49 | 0.13 | 0.47 |
| Belgium | 1.71 | 0.01 | 0.15 |
| Canada | 1.29 | 0.61 | 1.16 |
| Denmark | 0.39 | 2.46 | 1.99 |
| France | 6.94 | 8.17 | 8.44 |
| Germany | 4.72 | 0.59 | 1.98 |
| Italy | 6.32 | 4.88 | 5.90 |
| Japan | 18.13 | 28.22 | 21.73 |
| Netherlands | 1.45 | 0.01 | 0.02 |
| Spain | 3.93 | 7.63 | 5.32 |
| Sweden | 0.27 | 8.31 | 2.97 |
| United Kingdom | 6.42 | 11.95 | 7.65 |
| United States of America | 37.55 | 17.63 | 32.82 |
| **Panel B: Emerging economies** | 9.39 | 9.39 | 9.39 |
| Argentina | 0.02 | 0.29 | 0.09 |
| Brazil | 0.87 | 0.27 | 0.44 |
| Chile | 0.09 | 0.02 | 0.08 |
| China | 3.31 | 0.65 | 1.39 |
| Colombia | 0.23 | 0.18 | 0.30 |
| Czech Republic | 0.14 | 0.01 | 0.02 |
| Dominican Republic | 0.01 | 0.61 | 2.75 |
| Hungary | 0.16 | 0.16 | 0.19 |
| India | 1.48 | 2.91 | 1.71 |
| Indonesia | 0.49 | 0.60 | 0.40 |
| Malaysia | 0.23 | 0.02 | 0.05 |
| Mexico | 0.56 | 2.32 | 0.75 |
| Peru | 0.10 | 0.02 | 0.03 |
| Philippines | 0.01 | 0.87 | 0.41 |
| Poland | 0.39 | 0.01 | 0.03 |
| Romania | 0.11 | 0.02 | 0.07 |
| Russian Federation | 0.28 | 0.18 | 0.20 |
| South Africa | 0.39 | 0.15 | 0.18 |
| Thailand | 0.33 | 0.03 | 0.13 |
| Turkey | 0.19 | 0.06 | 0.14 |
| Uruguay | 0.01 | 0.01 | 0.03 |

Note: This table reports the average weight of each country in the BAU portfolio and the NZ portfolios with 10% and 5% reduction targets.

Table A.6: Minimisation of the Tracking Error: Financial Performance

| | BAU portfolio | NZ portfolio 10% reduction | NZ portfolio 5% reduction |
|---|---|---|---|
| **Panel A: General performance** | | | |
| Annual active share | – | 37.3% | 16.0% |
| Annual turnover | 0.0% | 16.5% | 10.1% |
| Average rating | 17.19 | 16.67 | 16.88 |
| Reduction in carbon intensity | -14.1% | -41.0% | -22.6% |
| Reduction in GHG emissions | -4.3% | -60.8% | -18.7% |
| **Panel B: Performance of hedged portfolio** | | | |
| Annual return | 3.19% | 2.94% | 3.10% |
| Annual volatility | 3.03% | 2.96% | 2.97% |
| Ex post Sharpe Ratio | 1.05 | 0.99 | 1.04 |
| Annual tracking error | – | 0.91% | 0.31% |
| **Panel C: Performance of unhedged portfolio** | | | |
| Annual return | 3.11% | 2.68% | 2.95% |
| Annual volatility | 4.27% | 5.16% | 4.47% |
| Ex post Sharpe Ratio | 0.73 | 0.52 | 0.66 |
| Annual tracking error | – | 1.55% | 0.43% |

Note: Panel A of this table reports some characteristics of the BAU portfolio and the NZ portfolios with 10% and 5% reduction targets, the average annual share, the annual turnover the average rating, the reduction in carbon intensity and in GHG 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.

Table A.7: Minimisation of the Tracking Error: Optimal Weights with Constraints

| | BAU portfolio | NZ portfolio 10% reduction | NZ portfolio 5% reduction |
|---|---|---|---|
| **Panel A: Advanced economies** | 90.61 | 90.61 | 90.61 |
| Australia | 1.49 | 0.80 | 0.92 |
| Belgium | 1.71 | 0.86 | 0.86 |
| Canada | 1.29 | 0.85 | 1.21 |
| Denmark | 0.39 | 0.58 | 0.52 |
| France | 6.94 | 10.40 | 9.92 |
| Germany | 4.72 | 5.20 | 3.39 |
| Italy | 6.32 | 8.10 | 5.84 |
| Japan | 18.13 | 26.08 | 23.15 |
| Netherlands | 1.45 | 0.73 | 0.74 |
| Spain | 3.93 | 5.68 | 5.36 |
| Sweden | 0.27 | 0.40 | 0.39 |
| United Kingdom | 6.42 | 9.49 | 8.64 |
| United States of America | 37.55 | 21.45 | 29.67 |
| **Panel B: Emerging economies** | 9.39 | 9.39 | 9.39 |
| Argentina | 0.02 | 0.02 | 0.02 |
| Brazil | 0.87 | 1.16 | 0.80 |
| Chile | 0.09 | 0.11 | 0.10 |
| China | 3.31 | 2.07 | 2.61 |
| Colombia | 0.23 | 0.29 | 0.24 |
| Czech Republic | 0.14 | 0.07 | 0.09 |
| Dominican Republic | 0.01 | 0.01 | 0.01 |
| Hungary | 0.16 | 0.12 | 0.16 |
| India | 1.48 | 2.12 | 1.99 |
| Indonesia | 0.49 | 0.71 | 0.67 |
| Malaysia | 0.23 | 0.13 | 0.20 |
| Mexico | 0.56 | 0.84 | 0.81 |
| Peru | 0.10 | 0.14 | 0.12 |
| Philippines | 0.01 | 0.01 | 0.01 |
| Poland | 0.39 | 0.20 | 0.24 |
| Romania | 0.11 | 0.13 | 0.11 |
| Russian Federation | 0.28 | 0.18 | 0.25 |
| South Africa | 0.39 | 0.50 | 0.46 |
| Thailand | 0.33 | 0.41 | 0.37 |
| Turkey | 0.19 | 0.17 | 0.15 |
| Uruguay | 0.01 | 0.01 | 0.01 |

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

Table A.8: Minimisation of the Tracking Error: Financial Performance with Constraints

| | BAU portfolio | NZ portfolio 10% reduction | NZ portfolio 5% reduction |
|---|---|---|---|
| **Panel A: General performance** | | | |
| Annual active share | – | 21.1% | 13.3% |
| Annual turnover | 0.0% | 5.3% | 7.5% |
| Average rating | 17.19 | 16.60 | 16.90 |
| Reduction in carbon intensity | -14.1% | -29.7% | -22.6% |
| Reduction in GHG emissions | -4.3% | -37.5% | -18.7% |
| **Panel B: Performance of hedged portfolio** | | | |
| Annual return | 3.19% | 3.20% | 3.09% |
| Annual volatility | 3.03% | 2.95% | 2.98% |
| Ex post Sharpe Ratio | 1.05 | 1.08 | 1.04 |
| Annual tracking error | – | 0.64% | 0.42% |
| **Panel C: Performance of unhedged portfolio** | | | |
| Annual return | 3.11% | 2.86% | 3.00% |
| Annual volatility | 4.27% | 4.89% | 4.56% |
| Ex post Sharpe Ratio | 0.73 | 0.59 | 0.66 |
| Annual tracking error | – | 1.02% | 0.61% |

Note: Panel A of this table reports some characteristics of the BAU portfolio and the NZ portfolios with 10% and 5% reduction targets, the average annual share, the annual turnover the average rating, the reduction in carbon intensity and in GHG 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.

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