A framework to align sovereign bond portfolios with net zero trajectories

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Abstract

Asset owners and asset managers have a key role to play in the global transition towards a low-carbon economy, and their actions have been coming under increasing scrutiny by the public. Hence, methodologies to examine the alignment of assets with net zero trajectories are becoming a necessity for all investors. The question is how to build a net zero portfolio without incurring financial risks across different asset classes. New methodologies have been emerging for equity and corporate bond portfolios to gauge and manage these risks. They include common frameworks such as the EU Paris Aligned Benchmark and the EU Climate Transition Benchmark. However, no common framework has been developed yet for sovereign bonds.

Nevertheless, sovereign bonds are one of the largest asset classes. It is thus paradoxical that there is very scarce literature available on sovereign portfolio net zero alignment. In our view, there is an urgent need to address this problem since governments now have the levers to influence all economic players to take environmental issues into account.

In this paper, we propose an alignment framework for sovereign bond portfolios, comprising definitions, databases, metrics and models. We then apply our framework to a global universe.[1]

Keywords: net zero portfolios, decarbonisation, transition, sovereign bonds alignment, portfolio alignment, climate change

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Introduction

In recent years, asset owners and asset managers have been grappling with the subject of climate change and this topic is likely to become even more important going forward. A large number of investors have signed the main net zero alliances that form the Glasgow Financial Alliance for Net Zero (GFANZ), which was created in 2021 to develop frameworks and methodologies helping financial institutions to accelerate the decarbonisation process and encourage them to make firm net zero commitments. There are now eight alliances for the various sectors with a total of 550 members from the investment community. It is now critical to develop frameworks and methodologies to support this initiative and facilitate the inclusion of extra-financial criteria in investment portfolios. However, we cannot reduce what we cannot measure. Regretfully, there are still no common market conventions to account carbon emissions for sovereign bond portfolios. While climate benchmarks like the EU Paris Aligned Benchmark and the Climate Transition Benchmark are widespread on equities, no clear benchmark is available for sovereign bonds. That is why investors tend to exclude sovereign bond portfolios from their decarbonisation commitments.

This is paradoxical because governments are key players in the global transition towards a low carbon economy. On the occasion of the Paris Agreement, 196 parties committed themselves to limiting the increase in temperature well below 2°C above pre-industrial levels and to pursue efforts to limit the increase in temperature to 1.5°C compared to pre-industrial levels[1]. Thus, the decarbonisation of our economies is a top-down process in which international cooperation is crucial to achieve an orderly transition. Moreover, according to the Intergovernmental Panel on Climate Change (IPCC), limiting the global temperature rise to 1.5°C by 2100 implies reaching net zero emissions by around 2050 [1]. The European Council formally adopted the European Climate Law in June 2021. Consequently, achieving net zero by 2050 is now legally binding for all countries in the European Union. The law also includes a greenhouse gas (GHG) emission reduction target of 55% for 2030 compared to 1990. More broadly, in the context of the 2015 Paris Agreement, each country has been requested to disclose its climate action plan to reduce carbon emissions, the so-called Nationally Determined Contributions (NDCs). These commitments are public and countries are required to update their commitments every five years. Net zero emission targets for individual countries is therefore a reality, which must be taken into consideration when building investment portfolios. Data availability is also improving day by day, as result of new agreements and regulations.

On the research side, portfolio construction with environmental constraints is a relatively new field that is expanding fast. Increasing data availability, new commitments by money managers (including the central banks) and the massive investment plans announced by governments since the COVID-19 pandemic are key factors behind this. In the equity space, Environment, Social and Governance (ESG) metrics for security selection have been applied for years. But the application of ESG constraints to sovereign bond portfolios has so far been limited, especially when it comes to climate-related issues. Nevertheless, sovereign bonds are one of the largest asset classes for institutional investors. Indeed, the market value of the Bloomberg Global Aggregate Treasuries is over USD30trn, and according to the Global Pension Assets Study (2023) [2], the bond allocation of pension funds ranged from 30% in the US to 55-60% in Japan and the UK in 2022. It is thus critical to align sovereign bond portfolios, not only because this is a major asset class but also because this provides an incentive for governments to make their economies greener and more environmentally sustainable, which generates positive externalities and establishes standards for all economic players.

One of the reasons for the absence of environmental constraints on sovereign bond portfolios is related to the fact that the EU taxonomy regulation does not apply to bonds issued by sovereign entities, supranational organisations or agencies. In fact, in 2021, the three European Supervisory Authorities (ESA[2]) concluded that "*there is no appropriate methodology to assess the taxonomy alignment of sovereign bond portfolios*". Furthermore, investors must be prepared to cope with changes in the EU taxonomy, that may include sovereign bonds in the future. This field of research is therefore likely to become increasingly important, with concrete applications for investors.

On top of the legal constraints to reach net zero emissions by 2050 in the EU, sovereign bond investors can be affected by two types of indirect climate risks: transition risks and physical risks. These climate risks can clearly end up being financial risks for investors. Transition risks arise from the adaptation cost to make the transition to a low carbon economy, while the physical risks are related to the marked increase in the magnitude and frequency of climate crises such as droughts, floods, wildfires and rising sea levels. Many studies have explored the link between the physical and financial risks for sovereigns. For example, Boehm (2022) [3] shows that rising temperatures can significantly affect the sovereign creditworthiness of emerging countries. Similarly, Kling et al. (2018) [4] have demonstrated that there is a positive relationship between climate vulnerability and the cost of debt. However, the assessment of climate transition risk is a more recent field, and there is scarce academic literature available on sovereign net zero alignment. Collender et al. (2022) [5] show that carbon emissions and greenness measures have a significant impact on sovereign bond yields. For portfolio alignment, Cheng et al. (2022) [6] propose a framework to decrease the carbon footprint of a sovereign bond portfolio, and provide a backward-looking analysis. To counter the lack of available resources to address this issue, a coalition of investors have launched the Assessing Sovereign Climate-related Opportunities and Risks (ASCOR) project to assess climate action plans and facilitate the alignment of sovereign bond issuers, but their final report has not been published yet.

The aim of our paper is to make a contribution to this nascent research field, by proposing an alignment framework for sovereign bond portfolios. The rest of the paper is organised as follows: we start by defining net zero portfolios. Then, we compare the different climate scenarios and decarbonisation trajectories. Next, we

[1] https://unfccc.int/process-and-meetings/the-paris-agreement

[2] The three ESA are the European Banking Authority (EBA), the European Insurance and Occupational Pensions Authority (EIOPA) and the European Securities and Markets Authority (ESMA).

provide a rundown of the various metrics and data sets for carbon emissions and greenness and expose several issues faced by investors when it comes to carbon accounting. In section 4, we define our alignment process and build a global net zero sovereign bond portfolio. We also investigate the different sets of constraints and common pitfalls to avoid. Finally, we analyse the financial risks that could potentially arise when aligning a sovereign bond portfolio: tracking risks, concentration risks and liquidity risks.

1 Net zero portfolio definition

According to the IPCC[1], we need to reach net zero emissions by 2050 to limit the temperature rise below 1.5°C by 2100, compared to pre-industrial levels [7]. The net zero state is reached when all carbon emissions are compensated using removal mechanisms, such as forest or carbon capture. The idea is then to reduce the bulk of carbon emissions and remove residual emissions that we cannot avoid. As it is mandatory to achieve net zero emissions to stabilise the temperature, investors will also have to adapt.

But if the physical state of net zero is clearly defined, there is no consensus about the definition of a net zero investment portfolio. Some financial actors only consider portfolio decarbonisation. Some others consider the average portfolio temperature offered by the main ESG data providers. This methodology is tempting because of its simplicity. But portfolio temperature methodologies are not yet mature enough. Other definitions of a net-zero portfolio consist in offsetting the portfolio's carbon footprint. Some investors build long-short portfolios to compensate the carbon footprint of the long leg with the carbon footprint of the short leg, but it represents an accounting trick and does not contribute to the net-zero physical state. Others use removal mechanisms such as carbon credits. This approach is increasingly criticised to the extent that it does not address the root causes of CO_2 emissions, offering a way to maintain polluting activities and just pay to compensate. There is also a time and geographical mismatch between CO_2 emitted and offset.

It is important to note that aligned portfolios are not net zero from day 1. Portfolios are aligned if they are in the right dynamic to achieve it in 2050. It is a portfolio of assets that are on the right pathway towards reducing their carbon footprint within a pre-defined trajectory that is compliant with the Paris Agreement. It is also a portfolio that contributes to greening the economy by developing or financing new technologies or industrial processes. Thus, aligning an investment portfolio consists in an incremental process where portfolios are adjusted through time to satisfy different criteria inspired by the four principles hereafter. In order to build a net zero portfolio, asset owners and managers need to:

Adopt a decarbonisation trajectory. According to the IPCC, limiting global warming to 1.5°C implies a carbon budget[2] of 500 $GtCO_2$ from 2020 to 2050 [8]. Thus, what is important is not the goal (net zero emissions in 2050), but the journey. To define the decarbonisation pace, asset owners and managers have to choose a climate scenario associated with a decarbonisation trajectory.

Favour actors with an active contribution to the climate transition. According to the International Energy Agency (IEA), it is necessary to reorient capital from fossil fuels to clean technologies to reach net zero before 2050 [9]. Thus, net zero alignment goes beyond portfolio decarbonisation. We have to consider a measure of greenness to favour actors providing solutions to tackle climate change. Considering greenness in the construction of net zero portfolios is also a way to benefit from the opportunities generated by the transition towards a low carbon economy.

Favour actors with ambitious and robust decarbonisation plan. When financial actors engage in net zero portfolio alignment, they begin a long-term process. Thus, it is important to consider forward-looking metrics to limit useless portfolio moves. Using company or government commitments is a way to incorporate forward-looking measures. The difficulty is then to differentiate between realistic and unrealistic decarbonisation plans, to consider only achievable and ambitious objectives in the portfolio construction.

Favour actors who proved their ability to reduce their carbon emissions in the past. Portfolio decarbonisation can be achieved in two ways: the self-decarbonisation of the underlying assets and portfolio rebalancing. Self-decarbonisation stems from the decrease of carbon emissions of the portfolio underlyings between two rebalancing dates, while decarbonisation through rebalancing is achieved by weight adjustment. Investors should favour self-decarbonisation because this is the only way to have an impact on the real economy. Considering past carbon emissions is a way to give more importance to actors who tackle the issue of climate change.

We detail our net zero alignment process for sovereign bond portfolios in section 4.

2 Decarbonisation scenarios

The choice of a decarbonisation trajectory is a prerequisite to align a portfolio. However, it can be a challenging task because an infinity of decarbonisation pathways lead to a temperature rise below 1.5°C with a significant probability. Yet, some trajectories are widely used by financial actors. In this section, we consider climate scenarios from the International Energy Agency (IEA) and the Network for Greening the Financial System (NGFS), but this list is not exhaustive. We also describe EU PAB and CTB pathways which are not properly speaking climate scenarios, but can be used as decarbonisation trajectories.

[1] Intergovernmental Panel on Climate Change.

[2] The carbon budget is defined by the IPCC as "*the estimated cumulative amount of global carbon dioxide emissions that that is estimated to limit global surface temperature to a given level above a reference period, taking into account global surface temperature contributions of other GHGs and climate forcers*".

2.1 PAB and CTB trajectories

The EU Technical Expert Group (TEG) on Sustainable Finance disclosed its two climate benchmarks in 2019: the EU Climate Transition Benchmark (CTB) and the EU Paris Aligned Benchmark (PAB) [10]. The two trajectories have been designed to help investors to benchmark their portfolios regarding greenhouse gas emissions, and are widely used as underlying for Exchange-traded funds (ETFs). It is a common way to invest in net zero portfolios for investors. The EU PAB is more stringent than the EU CTB by design. The TEG report published in 2019 details the minimum requirements for equities and corporate bond portfolios, but sovereigns are not yet in scope. The methodology will be reassessed in the next TEG report and may include guidelines for sovereign bonds.

The minimum requirements consist in exclusions, green exposure, sectoral exposure and carbon intensity reduction. The benchmarks are associated with two different decarbonisation pathways:

- a first year decarbonisation step: at least 50% for the EU Paris Aligned Benchmark and at least 30% for the EU Climate Transition Benchmark,
- a year-on-year self-decarbonisation trajectory of at least 7%.

We can notice that an important part of the effort to reduce carbon emissions is done at the beginning of the net zero alignment process. Thus, it can be challenging to align a portfolio with a PAB trajectory because a large part of carbon reduction is achieved before the economy had the time to adapt to the climate transition. As shown in Barahhou et al. (2022) [11], this can expose aligned portfolios to financial risks such as large tracking errors, concentration risks and liquidity risks.

2.2 IEA scenarios

The International Energy Agency was founded in 1974 after the oil crisis, with a focus on oil supply security. After the COP 21[1] in 2015, the IEA decided to take up the subject of climate change and to integrate clean energies in its outlook. Since then, the agency has developed several climate scenarios and became a reference for asset owners and asset managers. Relying on a set of hypotheses like population and gross domestic product growth, commodity prices or technological breakthroughs, each scenario is associated with a decarbonisation pathway and a temperature rise.

2.2.1 Stated Policies Scenario and Announced Pledges Case Scenario

The Stated Policies Scenario (STEP) corresponds to a scenario where all countries meet their carbon reduction commitments. Only firm policies are taken into account. In the Net Zero by 2050: A Roadmap for the Global Energy Sector (2021) [9], the IEA shows that current policies imply a temperature rise of about 2.7°C in 2100, with a 50% probability.

In the Announced Pledges Case Scenario (APC), every country respects its net zero commitment perfectly and on time. 70% of global CO_2 emissions are covered by the current pledges. This scenario is more stringent than the STEP scenario and is consistent with a temperature rise of about 2.1°C in 2100 with a 50% probability [9]. It means that the current Nationally Determined Contributions[2] and all the net zero pledges are not sufficient to limit the global warming under 1.5°C in 2100.

These two climate scenarios do not lead to net zero before 2050 and thus cannot be used to build net zero investment portfolios. However, they are interesting benchmarks to monitor.

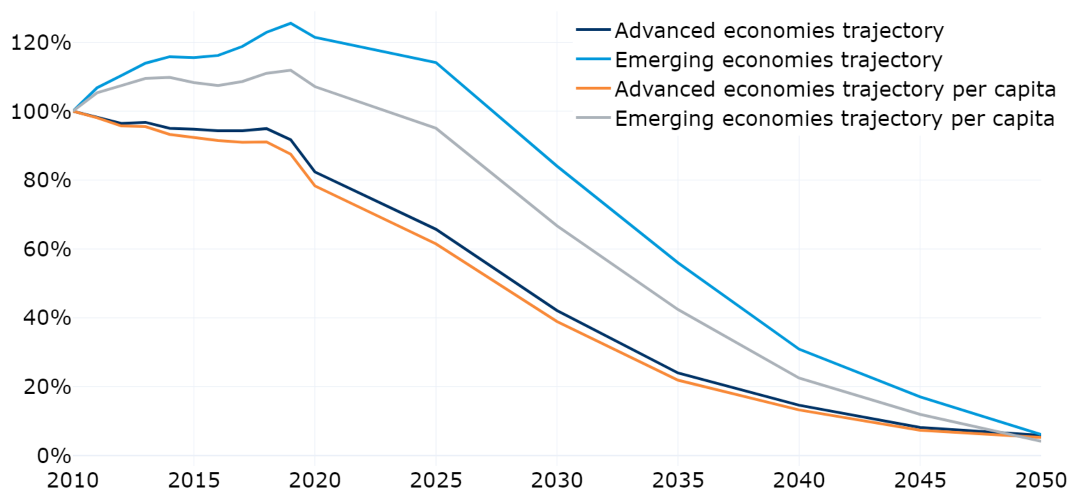
2.2.2 Net Zero scenario

The Net Zero Emissions by 2050 scenario (Net Zero Scenario) is consistent with a temperature rise of 1.5°C in 2100 with a 50% probability [9]. It shows one way to respect the Paris Agreement and details the different actions needed and a set of hypotheses to achieve this goal. A key advantage of using the IEA Net Zero Scenario for sovereign portfolio alignment is that it differentiates decarbonisation pathways for emerging and developed countries. It also differentiates between gross and net carbon emissions trajectories.

In this scenario, the carbon emissions peak is attained in 2019, and the decarbonisation pace increases significantly after 2025. Net zero is reached around 2045 in developed economies, and 2050 in emerging countries. No new oil and gas fields nor coal mines are built after 2021 and low-carbon hydrogen and carbon capture technologies are democratised after 2035. All new buildings are net zero carbon in 2030 and electricity production is net zero in advanced economies in 2035. Figure 1 gives the decarbonisation pathway in carbon emissions and carbon emissions over population for advanced and emerging economies.

[1] Conferences of the Parties.
[2] NDCs are better defined in section 3.3.1.

Figure 1: IEA Net Zero Trajectory



Source: IEA and authors' calculations

2.3 NGFS scenario

The NGFS[1] is a network of central banks and supervisors, sharing best practices on climate risk management. Launched in 2017, it counts 125 members and 19 observers worldwide. It has published six scenarios corresponding to different levels of transition and physical risks. The scenarios are split in four categories: orderly transition (low transition risk, low physical risk), disorderly transition (high transition risk, low physical risk), too little too late (high transition risk, high physical risk) and hot house world (high physical risk, low transition risk). The scenarios are the following:

- Net Zero 2050: this scenario is compliant with the Paris Agreement and leads to a temperature rise of 1.4°C. It results from an orderly transition;
- Divergent Net Zero: this scenario also leads to a temperature rise of 1.4°C but with higher costs due to divergent policies. It results from a disorderly transition;
- Below 2°C: leads to a temperature rise of 1.6°C with 64% chance of limiting it below 2°C. It results from an orderly transition;
- Delayed transition: leads to a temperature rise of 1.6°C, the first carbon emission reduction efforts are made after 2030. It results from a disorderly transition;
- Nationally Determined Contributions: in this scenario, every country respects its NDC, and it leads to a temperature rise of 2.6°C;
- Current Policies: in this scenario, only implemented measures are taken into account. This leads to a temperature rise above 3°C.

Hence, NGFS provide very interesting benchmarks allowing investors to assess the behaviour of their portfolios with different scenarios.

2.4 Comparing scenarios

Providers offer different levels of granularity and information regarding their scenarios. Nonetheless, we notice a lot of similarities. Both IEA and NGFS provide net zero scenarios, using different sets of hypothesis as input. The IEA STEP scenario is also very similar to the NGFS NDC scenario. The table below offers a comparison of the various scenarios.

[1] Network for Greening the Financial System.

Table 1: Scenario comparison

Source	Scenario	Description	Associated temperature rise
EU TEG	CTB	-30% year one then year on year decarbonisation of -7%	1.5°C
EU TEG	PAB	-50% year one then year on year decarbonisation of -7%	1.5°C
IEA	STEP	Each country meets its decarbonisation commitments, only fierce policies	2.7°C
IEA	APC	Each country meets its decarbonisation commitments	2.1°C
IEA	NZ	Net zero scenario	1.5°C
NGFS	NZ	Net zero scenario, orderly transition	1.4°C
NGFS	Divergent NZ	Divergent Net Zero, disorderly transition	1.4°C
NGFS	Below 2°C	Gradually increases the stringency of climate policies	1.6°C
NGFS	Delayed Transition	Efforts starts after 2030	1.6°C
NGFS	NDC	Each country meets its NDC	2.6°C
NGFS	Current Policies	Each country meets its decarbonisation commitments, only implemented policies	above 3°C

Source: EU TEG, IEA and NGFS

Remark. As NDC scenarios from the IEA and the NGFS lead to a temperature rise well above 1.5°C, it seems inevitable to use decarbonisation through rebalancing to build net zero sovereign bond portfolios.

3 Net zero metrics

The first challenge faced when assessing ESG characteristics in the sovereign bond space is the lack of reliable data. In this section, we detail different metrics and databases that can be useful when aligning a sovereign bond portfolio. All the metrics are not necessarily implemented in our models.

3.1 Carbon metrics

3.1.1 Carbon emissions

In contrast to carbon accounting for companies, we face a lack of standards for sovereign bonds. Many fundamental choices have to be made to estimate their carbon emissions. The first issue is the relevant scope to consider as explained by Domínguez-Jiménez and Lehmann (2021) [12]. Indeed, emissions from a sovereign issuer can be defined in two ways:

- Carbon emissions generated by the economic activities of the state, whether in its narrow definition[1] or its wider definition[2]. This methodology tends to underestimate carbon emissions and introduces a bias towards countries with small public sectors. However, it has the advantage of avoiding double counting.
- Carbon emissions generated on the geographical territory, which encompasses the sphere of influence of the sovereign but incorporates emissions from the private sector. This approach makes sense to the extent that the private sector operates under the rule of law defined by the sovereign. The difficulty with this methodology is to manage indirect carbon emissions through imports and exports. Indeed, if a company externalises overseas the most emitting economic activities, direct emissions will appear moderate while in fact they can be substantially higher if carbon intensive goods are imported.

We can either consider total carbon emissions, or split them into two categories:

- Carbon emissions from production: this methodology takes into account carbon emissions from all goods and services produced on the territory. It corresponds to the consumption of domestically-produced goods & services and exports. The drawback of this metric is that it favours countries that have relocated their emitting industries.
- Carbon emissions from consumption: this methodology takes into account carbon emissions from all goods & services consumed on the territory. It corresponds to the consumption of domestically-produced goods & services and imports. This accounting methodology allows to correct the bias generated by international trade.

As part of our study, we consider two main data sets provided by the International Monetary Fund (IMF). Climate Change Dashboard to assess countries' carbon emissions. The first one is the "CO_2 emissions embodied in Domestic Final Demand, Production, and Trade" data set which gives in particular CO_2 emissions from consumption and production. 2018 is chosen as the study year as it is the last one for which the data is available as of May 2023. The second one is the data set named "National Emissions Inventories and Targets" which provides emissions of five gases including greenhouse gas and carbon dioxide[3]. As of

[1] Central government.

[2] General government or non financial public sector which includes local administrations, regional states, state-owned companies, etc...

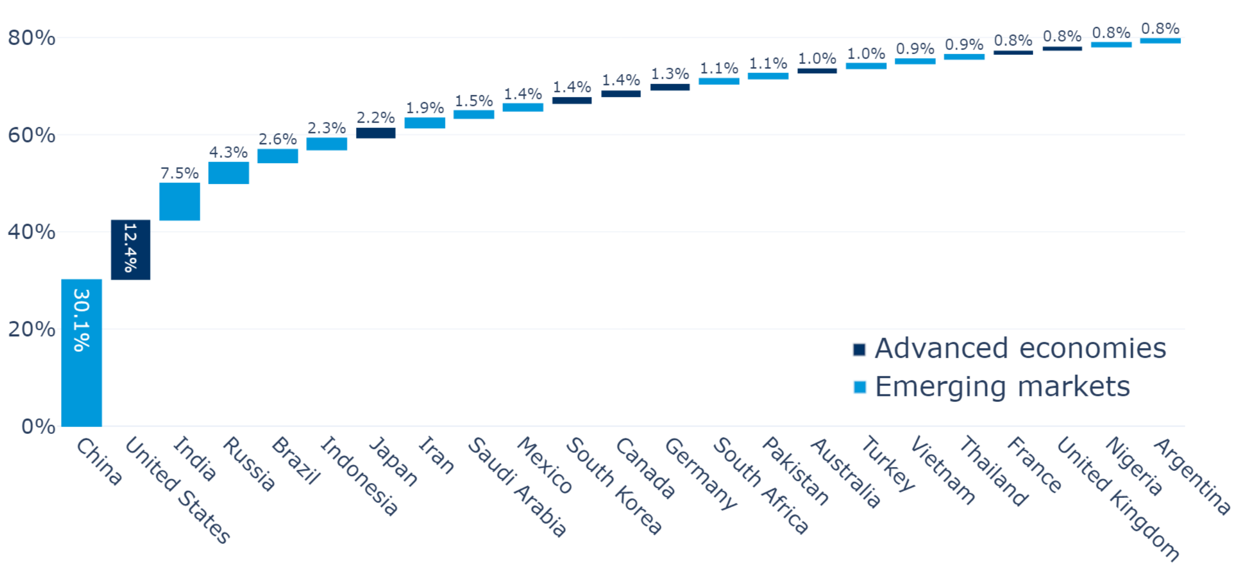
[3] Gases are split in 5 types: greenhouse gas, CO_2, nitrous oxide, methane and fluorinated gases.

May 2023, 2021 is the last available reference year.

Remark. The two carbon emission data sets may contain significant differences for some countries. In fact, the first one, containing CO_2 emissions from consumption and production, is obtained thanks to models and calculations, while the other one comes from country disclosure. Thus, this methodology distinction can imply unexplained discrepancies.

In Figure 2, we report the greenhouse gas emissions of the world's 23 largest carbon emitters. We notice that these 23 countries make up 80% of greenhouse gas emissions worldwide while the top ten represents over two thirds of these emissions. We split countries between advanced economies and emerging markets according to the World economic outlook (International Monetary Fund) (April, 2023) [13][1]. published in April 2023. This allows to see that advanced economies represent around 25.3% of worldwide greenhouse gas emissions for 13.4% of the population worldwide[2].

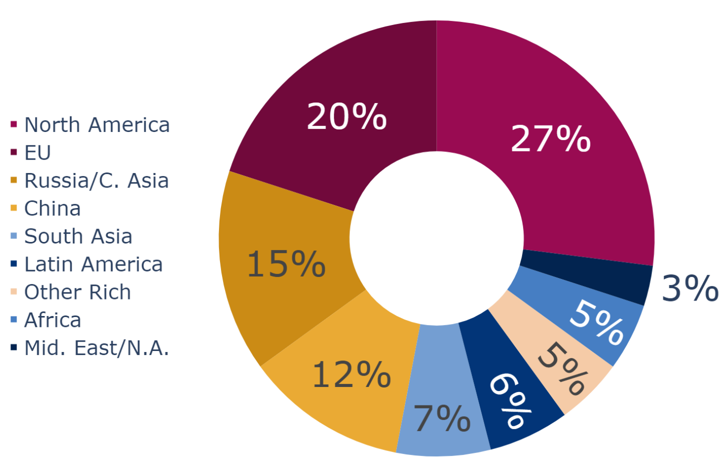
Figure 2: 23 countries make up to 80% of worldwide emissions in 2021



Source: IMF Climate Data & authors' calculations.

Nevertheless, we can challenge this hierarchy by looking at cumulative carbon emissions since the industrial revolution, using figures from Chancel and Picketty (2015) [14]. The US has the largest historical responsibility and remains the second largest emitter today. Meanwhile, China is estimated to be responsible for 12% of global cumulative emissions, but represents 30% of current emissions. In contrast, the share of the European Union has decreased over time. The EU is responsible for 20% of cumulative carbon emissions, but only represents half of this amount today.

Figure 3: Production-based cumulative emissions: breakdown by region since the industrial revolution



Source: Chancel and Picketty (2015) [14]

To compute the carbon emissions of an investment portfolio, we cannot naively compute the weighted average of carbon emissions. For instance, we cannot hold a portfolio only constituted by US treasuries accountable for all the emissions of the United States. A solution is to use a "portfolio emissions responsibility" scope using holding ratios. More precisely, let us denote $\mathcal{CE}^c_{portfolio}$, the carbon emissions embodied in the portfolio for country c, and $\mathcal{CE}^c$ the carbon emissions of country c, then we have

$$\mathcal{CE}^c_{portfolio} = \frac{\text{Portfolio investment in country } c}{\text{Gross Government Debt of country } c}\ \mathcal{CE}^c$$

[1]Referred to as WEO later.
[2]Using World Bank data.

We can then compute the carbon emissions embodied in the portfolio for all of the m countries present in the portfolio:

$$\mathcal{CE}_{portfolio} = \sum_{c=1}^{m} \mathcal{CE}^{c}_{portfolio}$$

This last notion can be seen as the transposition of the carbon footprint in the context of a sovereign bond portfolio. However, as explained by Raynaud (2015) [15], it is complicated to talk about ownership for sovereign bonds. In fact, it is not possible to engage with countries. Yet, if investors turn away from a country's sovereign securities, they can have a huge leverage on its government to give more attention to climate questions.

If it is somehow possible to compute carbon emissions linked to government bonds, it is very difficult to do so for local issuers like municipalities or provinces, and even more complicated for supranational emitters.

3.1.2 Carbon intensities

From a financial point of view, it seems a bit preposterous to compare and aggregate the carbon emissions of two countries with large differences of size or wealth as it will introduce important biases. Consequently, we need to normalise carbon emissions by a certain quantity to be able to compare them. Hence the concept of carbon intensity. Mathematically, we divide the carbon emissions (written $\mathcal{CE}$) by an indicator G to get the carbon intensity (written $\mathcal{CI}$), i.e.:

$$\mathcal{CI} = \frac{\mathcal{CE}}{G}$$

In the case of countries, three relevant indicators to consider are population, gross domestic product and public debt. Indeed, dividing "per capita"[1] seems better when trying to adopt a consumption-based point of view while dividing by the GDP looks more relevant when trying to adopt a production-based approach. We construct several metrics of CO_2 and GHG[2] emissions intensity using the consumption-based and production-based accounting. Mainly, we consider consumption-based metrics under the following form:

$$\mathcal{CI}_{(cons)} = \frac{\mathcal{CE}_{(cons)}}{Population}$$

expressed in tons of CO_2 equivalent per capita and production-based metrics under the following form:

$$\mathcal{CI}_{(prod)} = \frac{\mathcal{CE}_{(prod)}}{GDP_{const\$}}$$

expressed in tons of CO_2 equivalent per million USD of real GDP.

We can also normalize carbon emissions by the gross public debt of a country:

$$\mathcal{CI}_{(debt)} = \frac{\mathcal{CE}_{(total)}}{\text{Public debt}}$$

We do not use this metric in the rest of our study as it would bias our results towards highly indebted countries.

We use population and constant GDP data in US dollar from the World Bank database, using respectively the total population[3] and the constant dollar GDP[4]. Figure 4 provides the distribution of the CO_2 embodied in consumption per capita and the CO_2 embodied in production per GDP, using a logarithmic scale to reduce the dispersion and the range of intensities. Both distributions are calculated according to the level of development of the country: advanced economies vs emerging and developing economies. For both types of intensities, we can observe a shift of the distribution between advanced and developing economies.

When taking a "per capita" perspective, we observe two patterns: the distribution of emerging economies is shifted to the left, and is more spread out. It means that emerging countries tend to have more carbon-efficient consumption modes, but the way of consuming is heterogeneous among populations. The larger standard deviation of the emerging economies' consumption-based intensity can be explained as we mostly have South-Asian countries such as India, Myanmar, Cambodia or Laos on the left whereas at the other end of the distribution, we can find Gulf countries (Saudi Arabia, ...) or large polluters such as China or Russia. This also explains why advanced and emerging countries have overlapping distributions.

When taking a production-based point of view, the distribution of emerging countries is shifted to the right this time, due to relocation. Developed countries also tend to have less carbon-intensive production processes than emerging countries. At the left of the distribution, we find Western European countries (Sweden, the UK, France, Norway...) whereas at the right we tend to see large emerging economies such as the BRICS[5] (except Brazil).

[1] i.e. dividing by population.

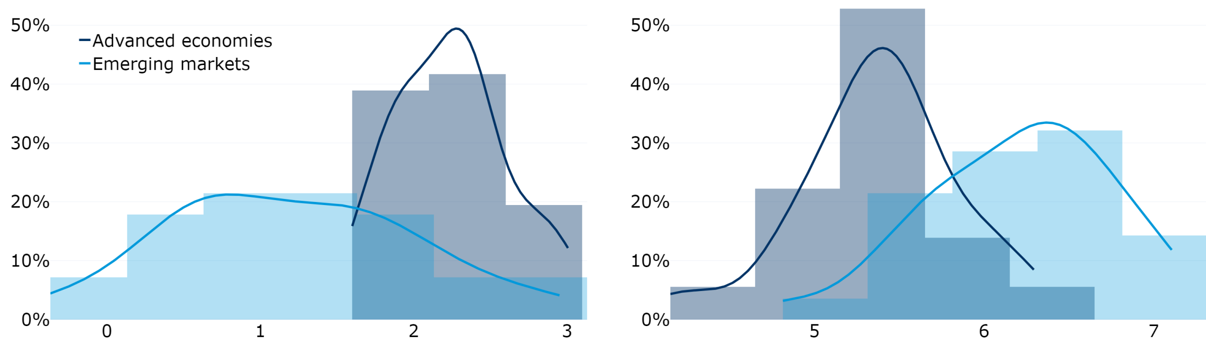
[2] Greenhouse gases is a broader concept than CO_2 to the extent that it includes methane, nitrous oxide and fluorinated gases.

[3] SP.POP.TOTL field.

[4] NY.GDP.MKTP.KD field.

[5] Brazil, Russia, India, China, South Africa.

Figure 4: Distributions of intensities by development level



(a) CO_2 from consumption over population log(tCO_2eq per capita)

(b) CO_2 embodied in production over GDP log(tCO_2eq per million dollar)

Source: IMF Climate Data, World Bank and authors' calculations

Figure 40 in the appendix shows the same dynamic for intensities built from GHG emissions. However, distributions are more widespread leading to an easier decarbonisation process.

Once we obtain our carbon intensities by country, we can compute a general portfolio carbon intensity by aggregating countries' intensities according to the country's weight in the portfolio. Therefore, if we denote m the number of different countries in our portfolio and w_j the weight in the portfolio associated to a country j[1] and $\mathcal{CI}_j$ the chosen carbon intensity of the j^{th} country, we have:

$$\mathcal{CI}_{(port)} = \sum_{j=1}^{m} w_j \, \mathcal{CI}_j$$

3.1.3 Carbon trends

In addition to looking at current carbon emissions or intensities, one can look at their trends to simulate future emissions or see the general dynamism of the historical emissions. We chose to adopt a linear trend model as done by Le Guenedal et al. (2022) [16], i.e. a model under the following form:

$$\mathcal{CE}(t) = \beta_0 + \beta_1 \, t + \varepsilon(t)$$

Coefficients β_0 and β_1 are estimated by the method of ordinary least squares. We can then build linear predictions of future emissions by extrapolating the past trajectory. Even though, the coefficient β_1 gives the general tendency of emissions, we still need to normalise this coefficient to be able to compare trends between different countries. This is why we divide β_1 by the carbon emissions corresponding to the last available year of historical emissions ($\mathcal{CE}_f$) to get the carbon normalised trends $\mathcal{CN}$:

$$\mathcal{CN} = \frac{\beta_1}{\mathcal{CE}_f}$$

We can also extrapolate carbon intensity trends, for both emissions per capita and emissions per GDP. However, extrapolating a ratio can sometimes be tricky as we can lose sight of what is physically happening.

Table 2 provides some statistics about carbon trends depending on the carbon metrics and differentiating between developed and emerging economies.

Table 2: Statistics of carbon normalised trends

		Carbon emissions			**Carbon intensities**			
	Group	$CO2_{cons}$	$CO2_{prod}$	GHG	$\frac{CO2_{cons}}{Population}$	$\frac{CO2_{prod}}{GDP}$	$\frac{GHG}{Population}$	$\frac{GHG}{GDP}$
Median	Advanced	-0.5%	-0.6%	-1.0%	-1.1%	-3.2%	-1.7%	-3.9%
	Emerging	2.6%	2.3%	1.5%	1.8%	-1.4%	0.0%	-2.3%
Negative	Advanced	60.6%	69.7%	69.7%	84.8%	100.0%	84.8%	97.0%
	Emerging	18.8%	15.6%	19.3%	21.9%	81.2%	49.7%	83.3%
Positive	Advanced	39.4%	30.3%	30.3%	15.2%	0.0%	15.2%	3.0%
	Emerging	81.2%	84.4%	80.7%	78.1%	18.8%	50.3%	16.7%
$< -1\%$	Advanced	30.3%	39.4%	45.5%	51.5%	97.0%	66.7%	97.0%
	Emerging	15.6%	12.5%	10.2%	12.5%	62.5%	31.3%	71.5%
$< -0.5\%$	Advanced	51.5%	51.5%	57.6%	60.6%	100.0%	75.8%	97.0%
	Emerging	18.8%	15.6%	15.3%	15.6%	81.2%	38.7%	75.7%
$> +0.5\%$	Advanced	33.3%	15.2%	15.2%	9.1%	0.0%	15.2%	3.0%
	Emerging	78.1%	75.0%	72.7%	75.0%	15.6%	40.5%	12.5%
$> +1\%$	Advanced	18.2%	9.1%	12.1%	6.1%	0.0%	6.1%	3.0%
	Emerging	75.0%	75.0%	58.0%	68.8%	15.6%	29.4%	7.6%

Source: IMF Climate Data, World Bank and authors' calculations

[1] More generally, we will call w_j weights in the portfolio referring to countries and x_i weights referring to bonds. See Table 17 in the appendix for more detail about the notations.

Comparing normalised trends of emissions and intensities can be done quite easily as countries have a long available track record. Generally, advanced economies have decreasing carbon emissions and intensities, i.e. negative trends ($\beta_1 < 0$), while emerging economies tend to have increasing carbon emissions, i.e. positive trends ($\beta_1 > 0$). This pattern is exacerbated by the fact that part of the developed countries' carbon reduction has been achieved through the relocation of highly emitting industries to emerging economies. For 60.6% of the developed countries in our sample, consumption trends of CO_2 emissions are negative ($\beta_1 < 0$). This figure increases to 69.7% for production trends. Table 2 also highlights that carbon intensities are decreasing faster than carbon emissions (i.e. the median of β coefficients is lower). Consistent with that, the table also shows a higher percentage of countries with decreasing intensities ($\beta_1 < 0$). For instance, all advanced countries have a CO_2 intensity from production with negative slopes. It is also worth noting that even though a majority of emerging countries have increasing carbon emissions, they also have decreasing production-based intensities[1]. This implies that their real GDP grows faster than their emissions. We can also point out that over 60%-75% of emerging economies have a carbon normalised trend over 1% for all three types of carbon emissions while only 15% have negative carbon emissions trends.

Once carbon normalised trends are computed for each country, we compute the carbon normalised trend of a portfolio as follows:

$$\mathcal{CN}_{(port)} = \sum_{j=1}^{m} \bar{w}_j \, \mathcal{CN}_j$$

where

$$\bar{w}_j = \frac{w_j \, \mathcal{CI}_j}{\mathcal{CI}_{(port)}}$$

We cannot directly use the country weights in the portfolio to compute its normalised carbon trend. $\bar{w}_j$ corresponds to the contribution of country j to the carbon intensity of the portfolio[2].

Remark: As stated by Barahhou et al. (2022) [11], considering carbon emissions or carbon intensities gives two very different pictures of carbon trends. Even if meeting net zero emission in 2050 implies meeting net zero intensity as well, the pathways to meet this objective are very different. Hence, the importance of the initial framework selection.

3.2 Greenness metrics

As portfolio alignment goes beyond carbon emissions reduction, there is also a need to provide greenness measures to implement the transition dimension. Unlike carbon emissions and intensities, defining a greenness metric is more challenging as there is no clear meaning of this notion. In this section, we explore different transition metrics, going from accounting metrics (green government spending and environmental taxes), to metrics assessing countries' willingness (commitments and participation to international conventions). We also mention the case of green bonds.

3.2.1 Government green spending

In the IEA Net Zero scenario, only 50% of carbon emissions reduction come from technologies that are mature today [9]. Thus, reaching net zero before 2050 requires new technologies that are not available today. To foster their development, the involvement of governments is fundamental. States have various levers at their disposal such as education, public funding, favourable tax regimes and regulations. For this reason, it is very important to consider government spending in the sovereign bond portfolio alignment process.

IEA Government Spending Data

Measuring the greenness of a country can be done by evaluating the extent to which governments finance a clean environmental transition. To design such a metric, we used the IEA's Government Energy Spending database [17]. This database is built on the latest approved policies and their fiscal contributions to the green transition, with a periodical update. This is particularly interesting as such capital expenditures have drastically increased in response to the COVID-19 pandemic and the global energy crisis, therefore reinforcing clean energy transitions. As of May 2023, the IEA tracks almost 1600 financial measures from 67 countries. These policies are divided into three types of funding sources - government, State Owned Entreprises/public institutions and private sector funds. Each policy is also assigned to one of 52 IEA's "tech categories", regrouping for example clean energy (wind, hydro), clean transportation (aircraft, buses, ships), energy storage (batteries, thermal storage), green buildings (efficient new builds), and efficiency (grids, energy efficiency).

To prevent biases due to the size of countries, we normalise these government expenses by GDP. Table 3 presents some examples of green public spending as a percentage of GDP.

[1] Intensities computed as the ratio of emissions to GDP.
[2] The full computation of the carbon normalised trend is available in Appendix B.1.

Table 3: Green budget spending as a percentage of the GDP

Country	Green spending (% of GDP)
Denmark	0.361%
Italy	0.153%
United Kingdom	0.131%
Australia	0.121%
South Korea	0.073%
Germany	0.069%
United States	0.066%
France	0.060%
Japan	0.014%
China	0.011%

Source: IEA, World Bank and authors' calculations

The portfolio greenness can then be written as:

$$\mathcal{GI}_{(port)} = \sum_{j=1}^{m} w_j \, \mathcal{GM}_j$$

where m denotes the number of different countries in our portfolio, $\mathcal{GM}_j$ the greenness metric value of the j^{th} country and w_j the weight of the j^{th} country in our portfolio. If it were possible to associate each bond to some green spending, it would be possible to adopt a bottom-up approach rather than a top-down one. That method would offer more precision concerning which bond effectively finances the transition.
Aside from looking at transition metrics from a static point of view, it would also be relevant to establish a dynamic measure of greenness. Nevertheless, it is difficult with this data set as it is fairly recent. But with more observations, it would be possible to track government spending over time and build a linear trend as we did for carbon emissions and intensities.

IMF Climate Change Dashboard

Another available data set is the IMF Climate Change Dashboard's Government Expenditure on Environmental Protection. It reports government expenditures on a specified set of activities including pollution, biodiversity, and waste and water management. This data set was built thanks to information available within the framework of the Classification of Functions of Government (COFOG). More precisely, the expenditures are divided into six categories, namely biodiversity and landscape protection, R&D, pollution abatement, waste management, waste water management and other expenditures. However, the main drawback of this data set is that no data is available for the United States, hence complicating its use for many investors. This is why we will not use this data set in the rest of our study. It is however interesting to mention that it offers a significant history which can be used to compute a greenness trend.

3.2.2 Green bonds

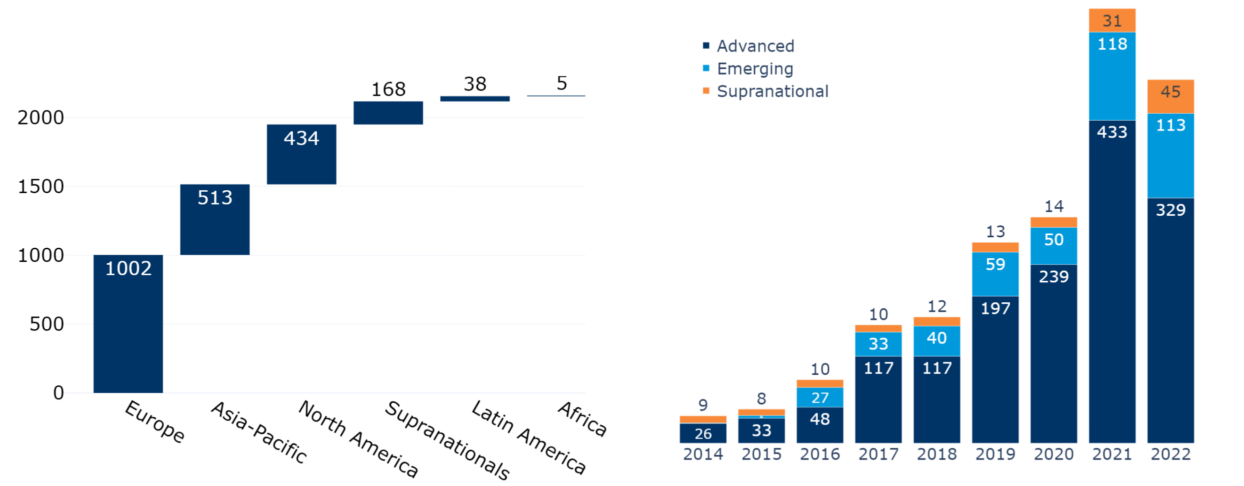
Another net-zero metric could refer to green bond issuance by sovereigns, which have been on the rise in recent years.

Beyond traditional ESG criteria for security selection, there is a typology of assets that is entirely dedicated to sustainable finance: green, social and sustainability-linked bonds. We will focus here on the former since the purpose of this paper is to achieve portfolio decarbonisation.

Green bonds have become an increasingly important tool to finance the fight against climate change. Originally related to the interest of Swedish institutional investors, the market took off in the late 2000s with inaugural issuances from development banks. In 2007, the European Investment Bank (EIB) issued the world's first Climate Awareness Bond to finance renewable energy projects and in 2008, the World Bank issued the first green bond.

Over the past 15 years, the market has grown exponentially but remains overall very small compared to conventional bonds. The volume of issuance was in the vicinity of $500-$550bn per year in 2021 and 2022 and the outstanding amount is $2300bn as of Q1-2023 according to the *Climate Bonds Initiative* (April 2023) [18]. The COVID years have been a turning point, with issuance volumes having more than doubled in 2021-2022 compared to 2018-2019 and sovereign issuers being more and more active. Issuance volumes by region and year are given by Figure 5.

Figure 5: Green bond issuance (in $bn)



(a) Cumulative regional issuance from 2006 to 2022 (b) Issuance by year and development level

Source: Michetti et al. (April 2023) [18] and https://www.climatebonds.net/market/data

Yet, the market value of the Bloomberg MSCI Global Green Bond index, which applies constraints in terms of quality, size and liquidity for security inclusion, is close to $1000bn. Meanwhile, the market value of the Bloomberg Global Aggregate index, a broad fixed income benchmark which is also restricted to investment grade securities and includes both corporate and sovereigns, is $66,200bn as we go to press, i.e. 66 times higher!

Green bonds vs conventional bonds

The main peculiarity of green bonds is the concept of "use of proceeds". Under the Green Bond Principles[1], the capital raised through a green bond should be affected to eligible green projects and there should be a defined process for project evaluation, selection and reporting. Green projects involve essentially energy, buildings, transport and water. These sectors represent almost 90% of the green bond market.

There are nonetheless some differences within green debt instruments. They can differ in the collateral assets and the recourse process in case of default. But the most common instrument, the green regular or the "use of proceeds" bonds, carries the same credit rating than a conventional bond to the extent that the bondholders have recourse to all the assets of the bond issuer. On the contrary, the recourse process of a green project bond for instance, only involves the assets related to the project.

The rise of sovereigns in the green bond market

Market participants have evolved significantly over the years. From a market that was initially supplied by development banks, issuance from the private sector (both financial and non-financial) took off markedly over the course of the past decade. Financial and non-financial corporates represented 55% of the issuance in the past two years, from 45% a decade ago.

But the major turnaround has been the rise of sovereign and government backed entities in the green bond market. In contrast to conventional bond markets, sovereign issuers were latecomers to the green bond market. This stems from the fungibility requirements of public debt frameworks in most countries, which conflict with use-of-proceeds earmarking of green bonds as stated by the BIS (2022) [19]. But since frameworks for sovereign green bond issuance have alleviated some of these difficulties, sovereigns have started to contribute significantly to the growth of the green bond market growth recently. From 0% a decade ago, sovereign issuance of green bonds represented almost 20% of volumes in 2022. Coupled with government-backed entities (20%), the supply of green bonds by public entities represented almost 40% of overall volumes last year.

Green bonds have a huge potential ahead. Clean energy investment support from governments has grown massively since the start of the COVID-19 crisis and is set to double in the coming years. According to the most recent IEA estimates, global energy investment, at $2.5-2.8 trillion at present, must almost double to reach net zero emissions by 2050.

From the perspective of investors, the amount of "green" money being poured by institutional investors, from pension funds to sovereign wealth funds and central banks, is likely to be huge in the coming years. In this context, what is called the "greenium", i.e. the lower yield of a green bond versus a conventional bond of similar characteristics, has room to fall further. It brings a borrowing cost advantage for the issuer and an opportunity for the investor if the "greenium" falls further, which involves capital gains. Recent studies find that, on average, green bonds trade four to eight basis points lower than conventional bonds. (Ando et al. (2023) [20], Caramichael and Rapp (2022) [21]). This "greenium" is linked to observable sources of demand pressure such as over-subscription and bond index inclusion.

We mainly define two ways of using green bonds as a greenness metric in our portfolio. For a portfolio originally containing green bonds, we can require the proportion of these green bonds to increase. However, it is not always the case. Therefore, another way is to define a greenness by country with green bonds. For

[1] Green Bond Principles are a taxonomy of green bonds provided by the International Capital Market Association.

a country j, we denote $\mathcal{GI}_j$ the ratio of the amount issued in green bonds over the total amount issued in bonds so that:

$$\mathcal{GI}_j = \frac{\text{Green bond issuance amount}}{\text{All bonds issuance amount}}$$

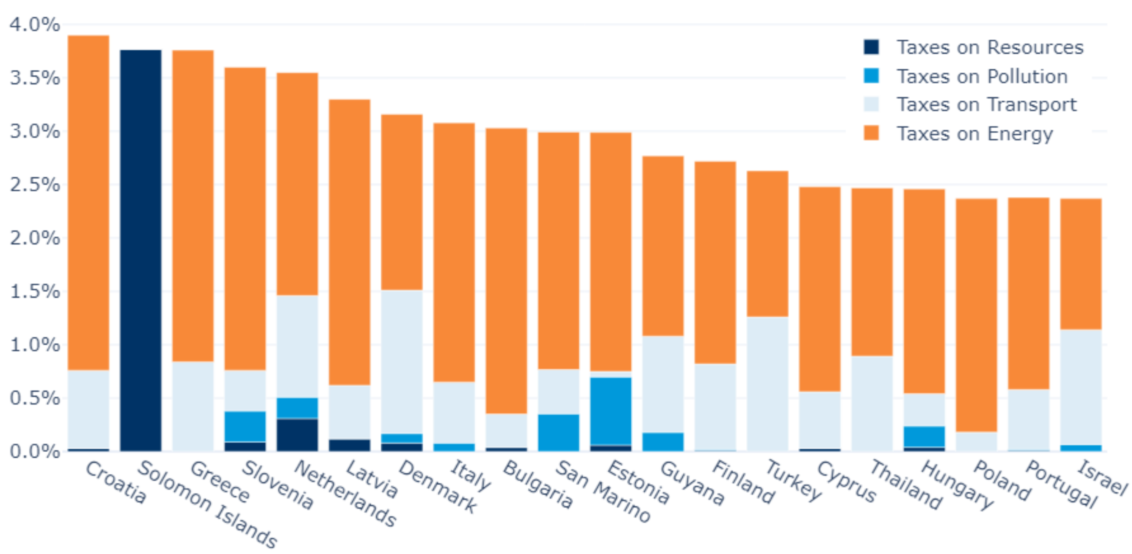
As done before, we can then define the greenness of the portfolio thanks to the weight by country w_j in the portfolio:

$$\mathcal{GI}_{(port)} = \sum_{j=1}^{m} w_j \, \mathcal{GI}_j$$

3.2.3 Environmental taxes

It is also interesting to look at environmental taxes to assess a country's willingness to tackle climate change. The IMF's Climate Change Dashboard offers such a data set. More precisely, environmental taxes are identified as a subset of taxes whose tax base is a physical unit (or a proxy of it) of something that has a proven, specific, negative impact on the environment, as defined in the System of National Accounts (2008) [22] and the Government finance statistics manual 2014 (2014) [23]. These environmental taxes are divided into four categories, respectively taxes on energy (including fuel for transport), taxes on transport (excluding fuel for transport), taxes on pollution and taxes on resources. Environmental taxes are also provided as a percentage of GDP for better comparability. It is interesting to note that countries facing higher physical climate risks tend to have a larger environmental tax share.

Figure 6: Environmental taxes by type and country



Source: IMF Climate Data

Again, we can compute the portfolio greenness according to this metric through the formula:

$$\mathcal{GI}_{(port)} = \sum_{j=1}^{m} w_j \, \mathcal{GM}_j$$

where m denotes the number of different countries in our portfolio, $\mathcal{GM}_j$ the environmental taxes value over the GDP of the j^{th} and w_j the weight of the j^{th} country in our portfolio. We can combine this static measure of the greenness with a dynamic one as substantial historical data is available.

3.3 Forward-looking and willingness metrics

3.3.1 Nationally Determined Contributions

Nationally Determined Contributions (NDCs) are commitments made by countries under the United Nations Framework Convention on Climate Change (UNFCCC) to reduce their greenhouse gas emissions and mitigate the effects of climate change. NDCs are intended to be both ambitious and achievable, and are designed to be updated and revised every five years to reflect each country's progress and changing circumstances. They play a crucial role in global climate action by providing transparency and accountability.

Key elements of NDCs typically include:

- **Emission reduction targets:** Countries specify their intended targets to reduce greenhouse gas emissions, typically in terms of percentage of reduction or specific emission levels to be achieved within a certain time frame.
- **Mitigation measures:** Countries outline the actions they plan to take to achieve their emission reduction targets. These measures can include policies, regulations, and initiatives to promote renewable energy, energy efficiency, sustainable transportation, and other climate-friendly practices.

- **Adaptation strategies:** Countries also address how they are willing to adapt to the impacts of climate change. This may include measures to enhance resilience in vulnerable sectors such as agriculture, water resources, infrastructure, and public health.
- **Support and capacity-building needs:** Developing countries often highlight their requirements for financial and technical assistance to implement their NDCs effectively. This support can come from other countries, international organisations, and climate funds established under the UNFCCC.

It is important to note that NDCs can widely vary across countries based on their specific circumstances and priorities, reflecting the principle of common but differentiated responsibilities and respective capabilities recognised in the Paris Agreement. As a matter of fact, all countries do not disclose their NDCs under the same format, hence the difficulty to compare them.

As an example, the EU[1] is committed to reducing its greenhouse gas emissions by at least 55% below 1990 levels by 2030, as part of its contribution to the Paris Agreement. It has developed a comprehensive set of policies and measures to achieve this target, including a carbon pricing system, renewable energy targets, and energy efficiency standards for buildings and appliances. It has also established a framework for monitoring and reporting progresses towards its NDC, to ensure both transparency and accountability.

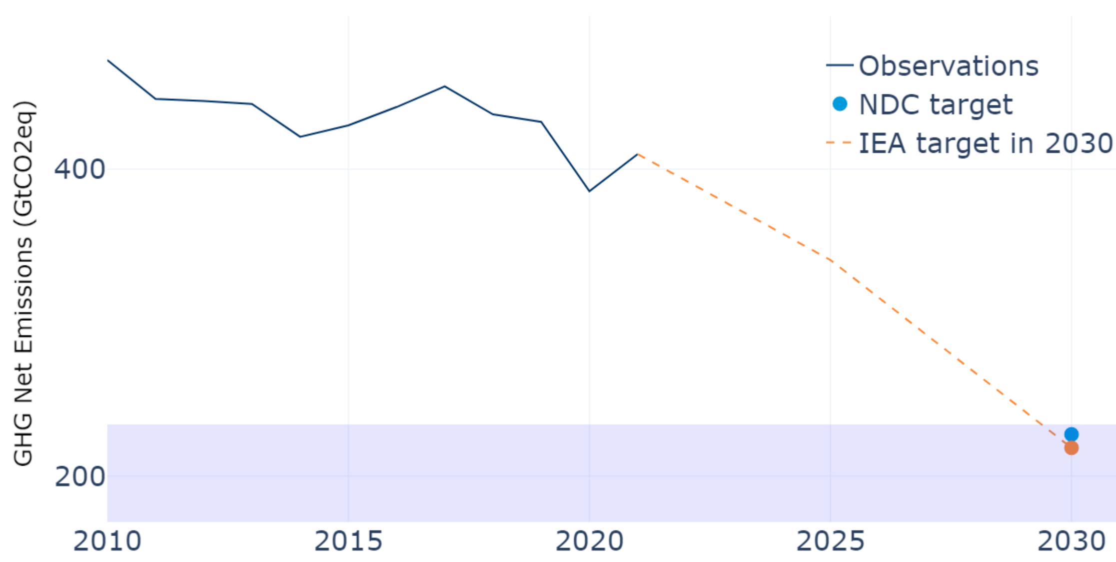
3.3.2 Assessment of countries' carbon emissions commitments

As portfolio alignment is a long-term incremental process, it is important to consider forward-looking metrics in the alignment procedure. Country's NDCs and commitments can be used to implement such metrics. But not all countries wish to participate to the same extent to the decarbonisation effort. This is why it is important to measure each NDC ambition, in order to prevent the overweighting of a country with unambitious targets.

Our goal is thus to establish a methodology to compare NDCs' greenhouse gas reduction to the net zero scenario, in order to assess how ambitious a NDC is. First, for each country, we express its commitments as a percentage of reduction of greenhouse gas emissions between a given base year and the NDC target year (here 2030). Then, we compare the obtained percentage to the chosen net zero scenario, leaving a 5% error margin.

In our study, we use the net zero scenario from the IEA as our reference scenario. As the IEA provides both a net zero scenario for advanced economies and emerging markets, we can get the list of countries in line with the IEA scenario according to their development level. This metric is illustrated by the following graph using France's emissions and NDC.

Figure 7: Comparison of France's NDC target to the IEA Net Zero scenario



Source: IMF Climate Data, IEA, UNFCCC and authors' calculations

The orange dashed-line matches France's emissions if it followed the IEA Net Zero Scenario starting in 2021. The blue point is France's targeted emissions in 2030 according to its NDC. The light-blue area corresponds to the tolerance area to qualify the NDC target as ambitious enough by allowing a 5% tolerance. The drawback of this metric is that a country can have a NDC above the reference scenario without being in breach with it. Given that most decarbonisation scenarios are at the global level, we would need granularity at the country level to correct this problem.

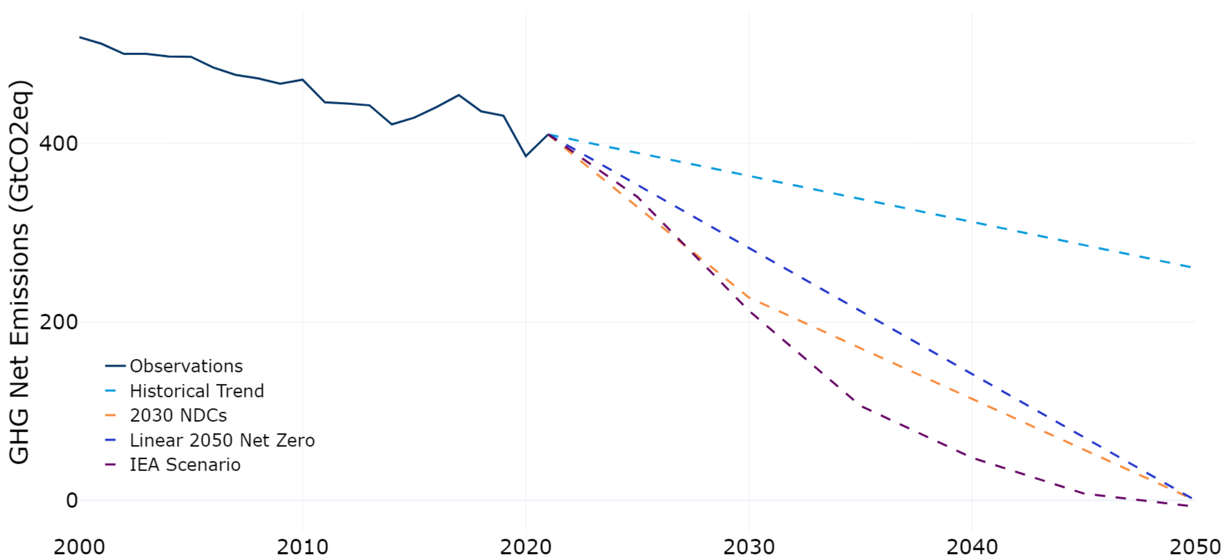
3.3.3 Evaluation of countries' progress towards their commitments

As mentioned in section 2, carbon reduction commitments are not sufficient to limit temperature rise below 1.5°C. It is thus all the more important to penalise countries that are not in line with their NDC in net zero portfolios.

[1]European Union.

To do so, we evaluate the gap between the carbon emissions targeted by the NDC and the corresponding emissions projected on the same year based on available historical emissions. We opted for a simple linear trend. We then keep the relative difference between the target and the projected value as a percentage. It is also possible to do the same thing with emissions per GDP and per capita.

Figure 8: France's predicted trends and other scenario estimations



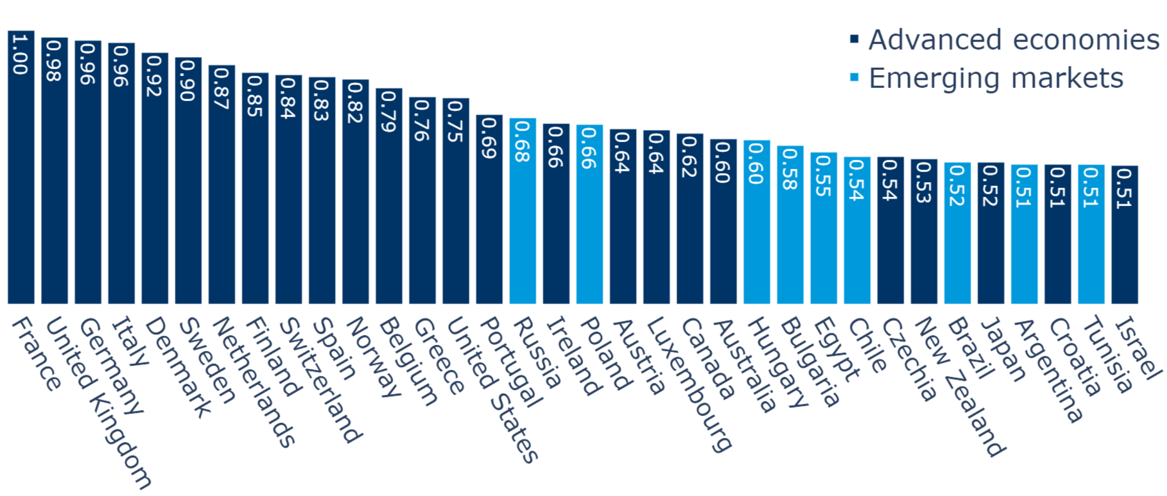
Source: IMF Climate Data, IEA, UNFCCC and authors' calculations

Figure 8 depicts France's net greenhouse gas emissions (in $GtCO_2eq$) and some possible ways to compare its future emissions and targets. The dashed light-blue line corresponds to the prediction of future carbon emissions based on the historical trend. We have also added the linear path to net zero in 2050, the IEA trajectory to net zero in 2050 and the trajectory according to France's 2030 NDC. The latter is built until 2030 to reach France's NDC target and then to reach linearly net zero in 2050. In order to assess how far countries are from their NDCs, we measure the relative distance between historical emissions projections and the corresponding NDC target. We take this measure at the last NDC target year. In our case, it is 2030. For the example shown in Figure 8, the NDC target in 2030 is 227 $GtCO_2eq$ when the current historical projection is 363 $GtCO_2eq$ leaving a relative difference of 37.5%.

3.3.4 Engagement in environmental conventions

It is also interesting to incentivise the more cooperative countries in net zero portfolios. To measure a government's sensitivity to climate issues, we can use one of the Notre Dame Global Adaptation Initiative (ND-GAIN) indicators, which measure engagement in international environmental conventions. ND-GAIN provides a score between 0 and 1 to each country based on its participation in international forums. As stated by ND-GAIN, the main rationale invoked by Chen et al. (2015) [24] is that "*the failure to take part in such forums is usually associated with either lack of technical capacity to deal with the issues and/or lack of political ability to reach decisions over appropriate engagement*". The score is then "*calculated as the ratio of a single country's current status of convention engagement to the maximum engagement among all countries*". Therefore, the closer to one, the better. The average country score is 0.29 with a 0.24 median.

Figure 9: Engagement in international environmental conventions - ND-GAIN indicator



Source: ND-Gain University Database

4 Alignment approach

Starting from a benchmark or an initial portfolio, our goal is to build the closest portfolio that satisfies net zero constraints. More precisely, benchmark portfolio optimisation consists in finding the optimal weight allocation to get a net zero investment portfolio while keeping similar financial characteristics. Therefore, we need to define both an objective function to minimise (or maximise) and a set of constraints that we require the portfolio to follow. After having explored objective functions, we will list various constraints to complete our problem.

We build our model around two main units: an objective function to minimise (or equivalently maximise) and linear constraints to satisfy. Formally, our optimisation problem can be written under the following form:

$$\begin{aligned} &\underset{x}{\textbf{minimize}} && f(x) \\ &\textbf{subject to} && \begin{cases} g_i(x) \leq 0, & i = 1, ..., \ell \\ h_j(x) = 0, & j = 1, ..., p \end{cases} \end{aligned}$$

f denotes the objective function, which is seen as a real function of the portfolio x (i.e. $f : \mathbb{R}^n \to \mathbb{R}$). The $(g_i)_{i\in\{1,...,\ell\}}$ functions represent the inequality constraints in our problem and the $(h_j)_{j\in\{1,...,p\}}$ functions represent the equality constraints. Sometimes, these optimisation problems are only presented with inequality constraints, as an equality constraint can be expressed as two inequality constraints.

4.1 Objective function

We consider two main objective functions to track the performances of a reference portfolio: the active share and the tracking error.

4.1.1 Active share

The active share measures the extent to which a portfolio's holdings deviate from the benchmark. It is defined as follows:

$$AS(x) = \frac{1}{2} \sum_{i=1}^{n} |x_i - b_i|$$

where x is a given portfolio and b our benchmark portfolio. We can then write our minimisation problem as:

$$\begin{aligned} x^\star = \; &\underset{x}{\textbf{argmin}} && \frac{1}{2} \sum_{i=1}^{n} |x_i - b_i| \\ &\textbf{subject to} && \begin{cases} Gx \leq h \\ Cx = d \end{cases} \end{aligned}$$

From a numerical point of view, a well-known and easily-solved class of optimisation problems are LP[1] problems. LP problems can be written under the following form:

$$\begin{aligned} &\underset{x}{\textbf{minimize}} && p^T x \\ &\textbf{subject to} && \begin{cases} Gx \leq h \\ Cx = d \end{cases} \end{aligned}$$

where x represents our portfolio of n assets, p, h and d are given vectors (of sizes n, ℓ and p) and G and C are respectively the matrix of inequality and equality constraints (of shapes $\ell \times n$ and $p \times n$). Even though the previous active-share problem is not an LP problem as it is, it can be turned into one. This is shown in Appendix B.2.

Linear optimisation problems can be solved in a limited time range even for problems with large number of entries. Thus, this formulation is useful to align bond portfolios as they tend to be large.

4.1.2 Tracking error

Another way of tracking an investment portfolio is through a tracking error minimisation. Let Σ denote the covariance matrix of total returns. We then define the tracking error variance as:

$$TE(x) = (x - b)^T \Sigma (x - b)$$

Using the TE, we can formulate our optimisation problem as:

$$\begin{aligned} x^\star = \; &\underset{x}{\textbf{argmin}} && \frac{1}{2}(x - b)^T \Sigma (x - b) \\ &\textbf{subject to} && \begin{cases} Gx \leq h \\ Cx = d \end{cases} \end{aligned}$$

This problem can be identified as a QP[2] problem, i.e. a problem of the following shape:

$$\begin{aligned} &\underset{x}{\textbf{minimize}} && \frac{1}{2} x^T Q x + x^T p \\ &\textbf{subject to} && \begin{cases} Gx \leq h \\ Cx = d \end{cases} \end{aligned}$$

[1] Linear programming.

[2] Quadratic programming.

where x represents our portfolio of n assets, Q is a positive symmetric matrix of shape $n \times n$, p, h and d are given vectors (of sizes n, ℓ and p) and G and C are respectively the matrix of inequality and equality constraints (of shapes $\ell \times n$ and $p \times n$). We can express tracking error minimisation problem as a QP problem with $Q = \Sigma$ and $p = -\Sigma b$. This is shown in Appendix B.3.

We adopted the active share minimisation problem for our simulations. In fact, tracking error algorithms are more time consuming than LP problems and numerical issues are unavoidable after attaining a critical size. Moreover, bonds' covariance matrices tend to be of bad quality due to the low liquidity of certain underlyings.

Standardisation of notations: From now on, we will design both functions under the notation f when the statements apply for the active share and the tracking error variance.

Remark. Several fundamental hypothesis are taken in this modelling approach. For example we suppose that bonds are infinitely divisible. We also suppose that liquidity is sufficient to rebalance our portfolio. Last but not least, we suppose that the whole benchmark structure[1] *is stable through time.*

4.2 Constraints

Portfolio alignment with net zero trajectory requires constraints of three natures:

1. **Weight and financial constraints**, such as weight deviation or duration constraints. It is often the minimum set of constraints that we will impose in all our problems.
2. **decarbonisation constraints**, like respecting a decarbonisation pathway given as an input.
3. **Transition constraints**, such as increasing the portfolio greenness or diminishing its normalised carbon trends.

We define our constraints' formulations in the following section. All of them can be written as linear constraints, meaning that they can be expressed thanks to two real matrices G and C (with respective dimensions $\ell \times n$ and $p \times n$) and two vectors h and d (respectively belonging to $\mathbb{R}^\ell$ and $\mathbb{R}^p$) by the following:

$$\begin{cases} Gx \leq h \\ Cx = d \end{cases}$$

Afterwards, b refers to benchmark's weights while x refers to our optimal weights. We use bold characters to refer to vectors.

4.2.1 Weight constraints

Constraints on weights by bond

We impose the aligned portfolio to be long-only with no leverage, i.e. mathematically speaking:

$$\mathbf{0}_n \leq \boldsymbol{x} \leq \mathbf{1}_n \quad \text{and} \quad \mathbf{1}_n^T \boldsymbol{x} = 1$$

where $\mathbf{0}_n$ and $\mathbf{1}_n$ respectively designate the vectors of size n only containing 0 and 1 values.

We can also impose a relative minimum or maximum deviation at the bond level using two non-negative reals λ^- and λ^+ such that:

$$\lambda^- \boldsymbol{b} \leq \boldsymbol{x} \leq \lambda^+ \boldsymbol{b}$$

Constraints on weights by country

To manage geographical diversification, we control the maximum weight deviation by country. Let $\delta^+ > 0$ be a relative upper bound, then we want for each country j to have:

$$\sum_{i \in Country_j} x_i \leq \delta^+ \sum_{i \in Country_j} b_i$$

More broadly, we can also implement minimum and maximum deviation constraints thanks to two functions (w_{min} and w_{max}) of the country weight. This allows us to give us more control on the weights to meet investors' requirements:

$$w_{min} \left(\sum_{i \in Country_j} b_i \right) \leq \sum_{i \in Country_j} x_i \leq w_{max} \left(\sum_{i \in Country_j} b_i \right)$$

In our simulations, we do not impose minimum weight deviation on bonds and countries as aligning is often synonymous with exclusions. It means that a bond or a country might be excluded compared to the reference portfolio if it has poor carbon and greenness metrics.

In the same manner, we might also set constraints on the distribution of economies in the portfolio by development level[2]. For instance, we can fix the proportion of advanced economies to a certain percentage p, where $p \in [0, 1]$. The corresponding constraint is:

$$\sum_{i \in Advanced} x_i = p$$

[1] Such as weights, country breakdown, duration, ratings, etc...
[2] i.e. distinguishing advanced and emerging economies.

It is also possible to set upper or/and lower limits for the proportion of advanced (respectively emerging) economies:

$$\sum_{i \in Advanced} x_i < p \qquad \text{or} \qquad \sum_{i \in Advanced} x_i > p$$

4.2.2 Financial constraints

As it is fundamental to keep some financial characteristics of the initial portfolio when performing the alignment process, we need to define constraints on the assets in our portfolio. When dealing with bonds, these constraints essentially take the form of duration, rating and yield constraints.

Duration constraints

While optimising its portfolio, an investor can adopt several approaches towards the bonds' duration. We give hereafter some examples that do not constitute an exhaustive list. First, a possible choice is to keep the same weight by bucket of duration. We formulate the duration constraint this way: for each bucket of duration j:

$$\sum_{i \in Bucket(j)} x_i = \sum_{i \in Bucket(j)} b_i$$

For such a constraint to be useful and efficient, one needs to define appropriate buckets[1]. We denote $\mathfrak{D}$ the set of the different duration buckets. It is also possible to adjust the average weighted duration of the new optimised portfolio as desired.

Rating constraints

In the same spirit, we can constrain the rating profile of the net zero portfolio by setting identical weights by ratings for each rating or bucket of ratings j:

$$\sum_{i \in Rating(j)} x_i = \sum_{i \in Rating(j)} b_i$$

We denote $\mathfrak{R}$ the set of ratings (resp. bucket of ratings[2]).

Yield constraints

One way of constraining yields is by imposing a lower bound and an upper bound on the weighted average yield[3]. Therefore:

$$y_{min} \leq \sum_i x_i \cdot y_i \leq y_{max}$$

y_{min} and y_{max} can be either set to chosen values or be defined as deviations to the weighted average yield, i.e. $y_{min} = (1 - \delta^-) \sum_i x_i \cdot y_i$ and $y_{max} = (1 + \delta^+) \sum_i x_i \cdot y_i$.

Remark. For all these financial constraints, we can add a tolerance parameter to allow a certain weight deviation compared to the original benchmark as it is less restrictive.

Once we have defined global constraints for our optimised portfolio, we can add constraints in relation to net zero metrics.

4.2.3 decarbonisation constraints

We can define portfolio decarbonisation using either carbon emissions or carbon intensity. To avoid a size bias, we use the carbon intensity in this study. One way to set decarbonisation constraints is to explain it relatively to a benchmark. Considering a reduction rate $\mathcal{R}$, we define the decarbonisation constraint as:

$$\mathcal{CI}(x) \leq (1 - \mathcal{R})\, \mathcal{CI}(b)$$

Some investors can also be interested in targeting a certain carbon intensity that depends on their commitments. In that case, we might want to set an upper bound $\mathcal{CI}^\star$ for the carbon intensity and write a constraint under the following form:

$$\mathcal{CI}(x) \leq \mathcal{CI}^\star$$

When choosing to decarbonise their portfolio, investors might want to make the distinction between advanced economies and emerging economies. In this case, the previous constraints are respectively replaced by two pairs of new constraints that can be written as:

$$\begin{cases} \mathcal{CI}_{adv}(x) & \leq & (1 - \mathcal{R}_{adv})\, \mathcal{CI}_{adv}(b) \\ \mathcal{CI}_{eme}(x) & \leq & (1 - \mathcal{R}_{eme})\, \mathcal{CI}_{eme}(b) \end{cases}$$

$$\begin{cases} \mathcal{CI}_{adv}(x) & \leq & \mathcal{CI}^\star_{adv} \\ \mathcal{CI}_{eme}(x) & \leq & \mathcal{CI}^\star_{eme} \end{cases}$$

[1] We used the following buckets for the Bloomberg Global Aggregate Treasuries: 0Y-2Y, 2Y-5Y, 5Y-10Y,10Y-20Y, 20Y+.
[2] We used the following buckets: Aaa - Aa - A - Baa - Ba - B - Caa - Ca - C.
[3] In our case, we used the yield to maturity.

where for a portfolio x, we denoted

$$\mathcal{CI}_{adv}(x) = \sum_{i \in Advanced} x_i \mathcal{CI}_i \quad \text{and} \quad \mathcal{CI}_{eme}(x) = \sum_{i \in Emerging} x_i \mathcal{CI}_i$$

Remark. We can adapt the previous reasoning for different decarbonisation metrics such as the carbon footprint.

4.2.4 Transition constraints

A portfolio which obeys the previous decarbonisation strategy is not necessarily a portfolio that is going to support the environmental transition. That is why we need to impose constraints to guarantee that the portfolio finances the transition towards a green economy.

Greenness constraint

Indeed, as shown in Table 4, there can be no correlation and even sometimes a positive correlation between greenness metrics and carbon intensities. For example, there is a clear positive relationship between carbon intensity from consumption and environmental expenditure. Thus, we need to introduce constraints on the greenness to ensure having a portfolio that finances the transition to a low-carbon economy.

Table 4: Correlation between transition and carbon metrics

	Env. Taxes[1]	**Env. Expend.**[2]	**Gov. Spending**[3]	**ND Gain Score**[4]
$\frac{CO2_{cons}}{Population}$	-6.44%	42.40%	0.98%	34.09%
$\frac{GHG}{Population}$	15.76%	15.67%	3.12%	-6.62%
$\frac{CO2_{prod}}{GDP}$	-5.20%	-32.66%	-18.66%	-40.44%
$\frac{GHG}{GDP}$	0.23%	-6.77%	-31.44%	-27.70%

Source: IMF Climate Data, IEA, ND-GAIN, World Bank and authors' calculations

We can adopt a symmetric approach to what was done for decarbonisation constraints. We select a green share increase rate $\mathcal{G}$ and control the greenness of the new portfolio compared to the existing benchmark:

$$\mathcal{GI}(x) \geq (1 + \mathcal{G}) \, \mathcal{GI}(b)$$

We can then implement a trajectory for the growth rate of the green share, or define it as a fixed rate.

In the following, we consider government environmental expenditures as our greenness measure. We use IEA data described in section 3.2.1.

Carbon trends

One common pitfall of portfolio decarbonisation is that it might lead to overweighting actors with upward trending carbon emissions. To avoid this situation, we impose constraints on carbon trends. The table below provides correlations between carbon trends and carbon/greenness metrics. It is interesting to note that greenness measures are all negatively correlated to each carbon trend, showing a virtuous relationship between our greenness metrics and carbon reduction dynamics.

Table 5: Correlation between normalised trends and other metrics

Intens.[5] \ **Trends**	**$CO2_{cons}$**	**$CO2_{prod}$**	**GHG**	**$\frac{CO2_{cons}}{Population}$**	**$\frac{CO2_{prod}}{GDP}$**	**$\frac{GHG}{Population}$**	**$\frac{GHG}{GDP}$**
$\frac{CO2_{cons}}{Population}$	-25.7%	-25.9%	-14.2%	-37.8%	-11.7%	-18.9%	2.1%
$\frac{GHG}{Population}$	0.1%	7.7%	8.1%	-10.5%	12.9%	4.4%	8.4%
$\frac{CO2_{prod}}{GDP}$	49.8%	52.6%	40.7%	55.4%	34.6%	39.9%	20.4%
$\frac{GHG}{GDP}$	63.1%	61.7%	15.9%	77.0%	45.3%	10.2%	10.0%
Env. Taxes	-60.0%	-54.3%	-17.2%	-47.1%	-25.5%	-5.0%	-6.5%
Env. Expend.	-51.4 %	-48.3%	-21.2%	-49.5%	-24.0%	-11.7%	-3.0%
Gov. Spending	-33.5%	-29.7%	-20.7%	-20.7%	-16.1%	-8.3%	-8.3%
ND Gain Score	-63.7%	-68.6%	-47.2%	-67.2%	-21.8%	-33.4%	-20.1%

Source: IMF Climate Data, IEA, ND-GAIN, World Bank and authors' calculations

Depending on the objective, different types of carbon trend constraints can be implemented. An investor might have to target a certain carbon trend in order to be on track with a given trajectory. For example, it can be interesting to target a carbon normalised trend of -7% corresponding to the minimum year-on-year decarbonisation rate of PAB and CTB trajectories. This way, we intend to increase the decarbonisation

[1] Environmental Taxes.
[2] Expenditures on environmental protection.
[3] IEA Government Energy Spending.
[4] ND Gain Convention participation score.
[5] "Intens." here designates either carbon intensities or transition metrics.

achieved by self-decarbonisation rather than rebalancing. If we name $\mathcal{CN}^\star$ the threshold we set for normalised carbon trends, we can express the constraint as:

$$\mathcal{CN}(x) \leq \mathcal{CN}^\star$$

Likewise, we can require a difference in the normalised trend value of $\mathcal{CN}^- \geq 0$ between the optimised portfolio and the benchmark.

$$\mathcal{CN}(x) \leq \mathcal{CN}(b) - \mathcal{CN}^-$$

Finally, we might also want to exclude all countries that have upward trending carbon emissions from the portfolio to prevent the greenwashing risk.

Remark. The same work can be done for greenness dynamic measures (i.e. trends on the greenness metrics).

It is also relevant to add some forward-looking constraints to complete our panel of transition constraints. We can adopt different approaches to do so. Our main objective is to favour countries that are both ambitious and on track with their ambitions.

NDC ambition

We chose to compare countries' NDCs in 2030 with the reference scenario (for us IEA Net Zero) in 2030 to assess if their commitments are ambitious enough. To do so, we discriminate countries between those whose NDC target emissions fall within a certain range around the value forecast by the IEA scenario and the others. We call this criterion $\mathcal{CAS}$[1]. Excluding countries that are not ambitious enough, i.e. countries who do not meet the $\mathcal{CAS}$ criteria, can be done by setting weights of bonds issued by these countries to zero in the optimised portfolio. However, this approach can be seen as too restrictive. Another more permissive possibility is to require the proportion of weights from countries in line with the scenario to increase. Implementing such a constraint can be done in the same way as greenness constraints.

NDC fulfilment

To favour countries on track with their target, we evaluate whether countries' historical trends are in line with their commitments. For each country, we project emissions with a linear trend and compare the projection to its NDC [2]. If the projection falls below the NDC, we consider that the country is on track to fulfil its NDC. We call this criterion $\mathcal{EOTC}$[3]. As when evaluating the $\mathcal{CAS}$ criteria, we can exclude all countries that do not currently satisfy the $\mathcal{EOTC}$ criterion or set a threshold for the proportion of countries that do respect this criterion. We can also require the optimised portfolio to be on track with what could be fathomed as an portfolio NDC target.

We recall that all the presented constraints can be written as linear constraints[4]. Thus, we can standardise notations for all of the constraints for the future definition of our optimisation problem by using the matrix form introduced before, i.e.:

$$\begin{cases} Gx \leq h \\ Cx = d \end{cases}$$

4.3 Optimization problems

Using the above constraints and objective functions, we can define different optimisation problems. Of course, all these problems can be adapted to meet investors' needs and demands.

4.3.1 Main optimisation problem

We start by building $\mathbf{C_0}$ the set corresponding to weight and financial constraints as follows:

$$\mathbf{C_0} = \Omega_1 \cap \Omega_2 \cap \Omega_3$$

where

$$\Omega_1 = \{x \in \mathbb{R}^n, \mathbf{0}_n \leq x \leq \mathbf{1}_n\} \cap \left\{x \in \mathbb{R}^n, \mathbf{1}_n^T x = 1\right\}$$

$$\Omega_2 = \bigcap_{c_j \in \mathfrak{C}} \left\{ w_{min} \left(\sum_{i \in c_j} b_i \right) \leq \sum_{i \in c_j} x_i \leq w_{max} \left(\sum_{i \in c_j} b_i \right) \right\} \bigcap \left\{ (1-\delta) \sum_{i \in adv} b_i \leq \sum_{i \in adv} x_i \leq (1+\delta) \sum_{i \in adv} b_i \right\}$$

$$\Omega_3 = \bigcap_{d_j \in \mathfrak{D}} \left\{ \sum_{i \in d_j} x_i = \sum_{i \in d_j} b_i \right\} \cap \left\{ y_{min} \leq \sum_i x_i y_i \leq y_{max} \right\} \bigcap_{r_j \in \mathfrak{R}} \left\{ \sum_{i \in r_j} x_i = \sum_{i \in r_j} b_i \right\}$$

with $\mathfrak{C}$, $\mathfrak{D}$ and $\mathfrak{R}$ respectively being the set of countries, duration buckets and rating buckets. Ω_1 corresponds to the long-only and no leverage constraints. The set Ω_2 contains constraints on weight by country and by development level while Ω_3 represents constraints on financial characteristics.

To this base set of constraints, we add the following constraints on the carbon intensity and greenness:

$$\begin{cases} \mathcal{CI}_{adv}(x) & \leq (1-\mathcal{R}_{adv})\, \mathcal{CI}_{adv}(b) \\ \mathcal{CI}_{eme}(x) & \leq (1-\mathcal{R}_{eme})\, \mathcal{CI}_{eme}(b) \\ \mathcal{GI}(x) & \geq (1+\mathcal{G})\, \mathcal{GI}(b) \end{cases}$$

[1] Commitments Aligned with the Scenario.
[2] i.e. countries whose linearly projected emissions currently fall short of their NDC target with a certain tolerance percentage.
[3] Emissions On Track with Commitments.
[4] Previously defined at the beginning of this section.

To ease the notations, we denote $\mathbf{C_1}$ the following set of constraints:

$$\mathbf{C_1} = \mathbf{C_0} \cap \left\{ x \in \mathbb{R}^n, \left| \begin{array}{rl} \mathcal{CI}_{adv}(x) & \leq (1-\mathcal{R}_{adv})\,\mathcal{CI}_{adv}(b) \\ \mathcal{CI}_{eme}(x) & \leq (1-\mathcal{R}_{eme})\,\mathcal{CI}_{eme}(b) \\ \mathcal{GI}(x) & \geq (1+\mathcal{G})\,\mathcal{GI}(b) \end{array} \right. \right\}$$

We obtain our main net zero alignment problem, that we call $(\mathbf{P_1})$. The solution $x^\star$ to problem $(\mathbf{P_1})$ is then defined by:

$$x^\star = \underset{x}{\textbf{argmin}} \quad f(x) \qquad \textbf{subject to} \quad x \in \mathbf{C_1} \tag{$\mathbf{P_1}$}$$

In this problem, we minimise $f(x)$ and require that x satisfies both maximum weight deviation and financial constraints. We also have a carbon intensity reduction rate of $\mathcal{R}_{adv}$ for advanced countries in the portfolio and of $\mathcal{R}_{eme}$ for emerging countries in the portfolio. Finally, we want the greenness of the newly obtained portfolio to be at least $1+\mathcal{G}$ times higher than the initial portfolio. In fact, setting a $\mathcal{G}$ coefficient above zero prevents the aligned portfolio to have decreasing green features.

4.3.2 Complete net zero alignment optimisation problem

As we seek to have optimised portfolios that fully answer our definition of a net zero portfolio, we continue adding new constraints to the previously expounded problem. More precisely, we supplement our problem with constraints on normalised trends and on the proportion of countries respecting the $\mathcal{CAS}$ and $\mathcal{EOTC}$ criteria[1]. To do so, we use a threshold value, respectively named $\mathcal{CN}^\star$, $\mathcal{CAS}^\star$ and $\mathcal{EOTC}^\star$, for each of the new constraint. This gives us our complete net zero alignment optimisation problem that we call $(\mathbf{P_2})$:

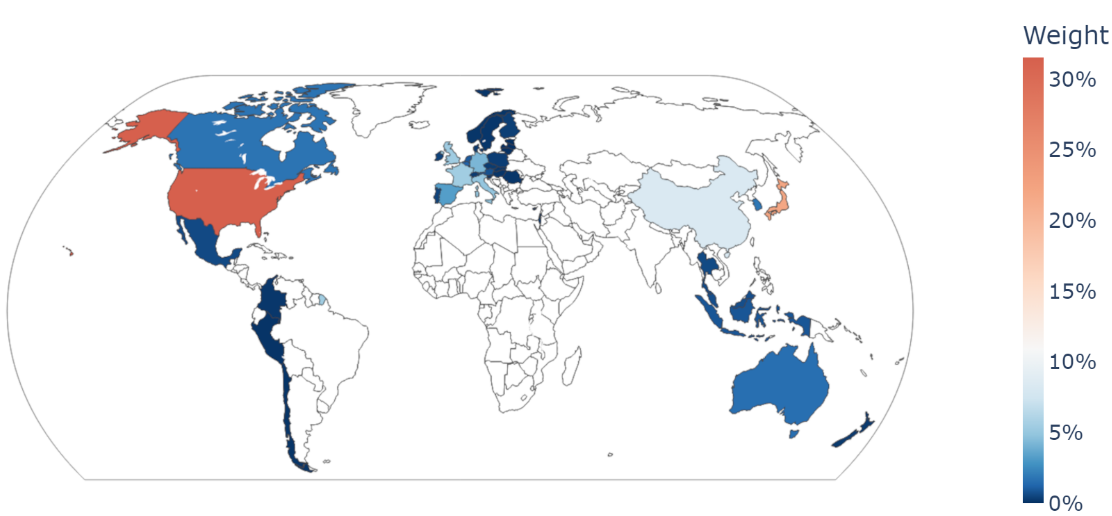
$$x^\star = \underset{x}{\textbf{argmin}} \quad f(x) \qquad \textbf{subject to} \quad \begin{cases} x \in \mathbf{C_1} \\ \mathcal{CN}(x) \leq \mathcal{CN}^\star \\ \mathcal{CAS}(x) \geq \mathcal{CAS}^\star \\ \mathcal{EOTC}(x) \geq \mathcal{EOTC}^\star \end{cases} \tag{$\mathbf{P_2}$}$$

Compared to the previous problem, this one tries to encompass more dimensions of the net zero portfolio definition given in section 1. In addition to decarbonisation and greenness constraints, we add the three net zero requirements which aim at having a higher self-decarbonisation rate. They also enable an important part of the portfolio to be in line with the net zero scenario and countries' future ambitions.

5 Investment universe

We consider the Bloomberg Global Aggregate Treasuries[2] composition as of 03/30/2023 as our initial portfolio. It is composed of 1802 sovereign bonds from 44 different countries among which 75% are considered advanced economies by the IMF [3]. In terms of weights in the portfolio, advanced economies constitute just over 88% of the index. Figure 10 gives an overview of the benchmark weight distribution by country. The allocation is concentrated on the United States, Japan, China and Western Europe.

Figure 10: Weight distribution by country in the Bloomberg Global Aggregate Treasuries

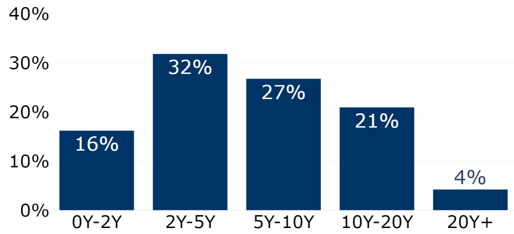


Source: Bloomberg and authors' calculations

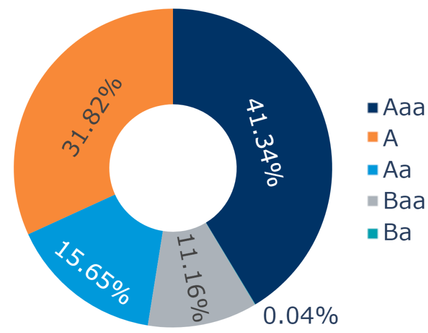
Figure 11 depicts the distribution of ratings[4] and duration in the Bloomberg Global Aggregate Treasuries. In the benchmark, ratings range from *Ba* to *Aaa*, and the majority of the issuers have very low credit risk.

[1] For a portfolio x, we call these proportions $\mathcal{CAS}(x)$ and $\mathcal{EOTC}(x)$.
[2] The index ISIN is LGTRTRUU.
[3] Cf. WEO[13].
[4] From Moody's.

Figure 11: Distributions of bonds' ratings and duration



(a) Distribution by bucket of duration



(b) Distribution by bucket of ratings

Source: Bloomberg, Moody's and authors' calculations

Aaa and *A* ratings constitute over 70% of the portfolio, with 40% of the issuers rated *Aaa*. This is mainly due to the US, Germany and Canada being rated *Aaa* and to Japan and China being rated *A*.

We compute the targeted carbon intensities using the last value available for each intensity metric. 2018 is the reference year for production and consumption carbon intensities, 2021 for the other intensity metrics. The net zero metrics of our reference portfolio are the following:

Table 6: Carbon intensities for the Bloomberg Global Aggregate Treasuries portfolio

	$\frac{\textbf{CO2}_{\textbf{cons}}}{\textbf{Population}}$	$\frac{\textbf{GHG}}{\textbf{Population}}$	$\frac{\textbf{CO2}_{\textbf{prod}}}{\textbf{GDP}}$	$\frac{\textbf{GHG}}{\textbf{GDP}}$
	tCO_2eq per capita		tCO_2eq per million \$	
All Countries	10.1	11.9	306.7	334.8
Advanced economies	9.4	10.8	234.4[1]	226.2
Emerging economies	0.7	1.1	72.3	108.6

Source: IMF Climate Data, World Bank and authors' calculations

For each country or group of countries c_j, we can compute its contribution to the carbon intensity[2]. For instance, for developed and emerging countries[3], we have:

Table 7: Contribution to carbon intensities for the Bloomberg Global Aggregate Treasuries portfolio

	$\frac{\textbf{CO2}_{\textbf{cons}}}{\textbf{Population}}$	$\frac{\textbf{GHG}}{\textbf{Population}}$	$\frac{\textbf{CO2}_{\textbf{prod}}}{\textbf{GDP}}$	$\frac{\textbf{GHG}}{\textbf{GDP}}$
Advanced economies	93%	91%	76%	68%
Emerging economies	7%	9%	24%	32%

Source: IMF Climate Data, World Bank and authors' calculations

Of course, as advanced economies constitute over 80% of the index, they contribute way more to the carbon intensity than emerging economies. On average, advanced economies' contribution to consumption-based carbon emissions is over 90% whereas it is around 70% for production-based carbon intensities. The difference between the two intensities is due to the fact that emerging countries tend to have lower emissions per capita than advanced economies as opposed to emissions per GDP.

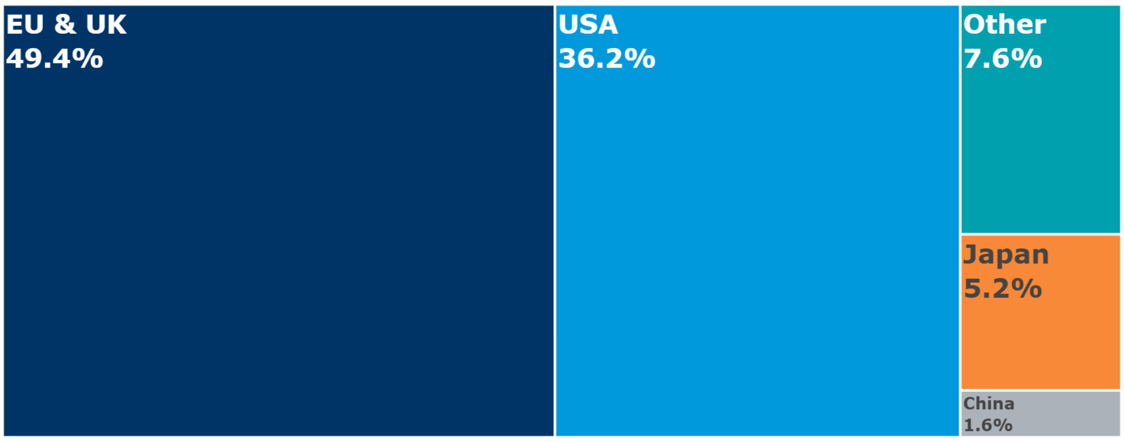
Net zero alignment is also strongly dependent on greenness metrics. Figure 12 shows the greenness distribution inside our reference portfolios. It is interesting to note that almost half of the greenness of the portfolio emanates from bonds issued by the European Union and the United Kingdom. The United States of America account for almost a third.

[1]The CO_2 per GDP intensity is greater than the GHG per GDP intensity. This is mainly due to a difference in the reference year (2018 vs. 2021) and discrepancies in the two data sets. See the remark in section 3.1.1 for more precision.

[2]The contribution to carbon intensity is evaluated as follows: $C_{\mathcal{CI}} = \frac{\sum_{i \in c_j} b_i \cdot \mathcal{CI}_i}{\mathcal{CI}(b)}$.

[3]We give the contribution to the GHG per GDP carbon intensity by region in Figure 41 in Appendix B.

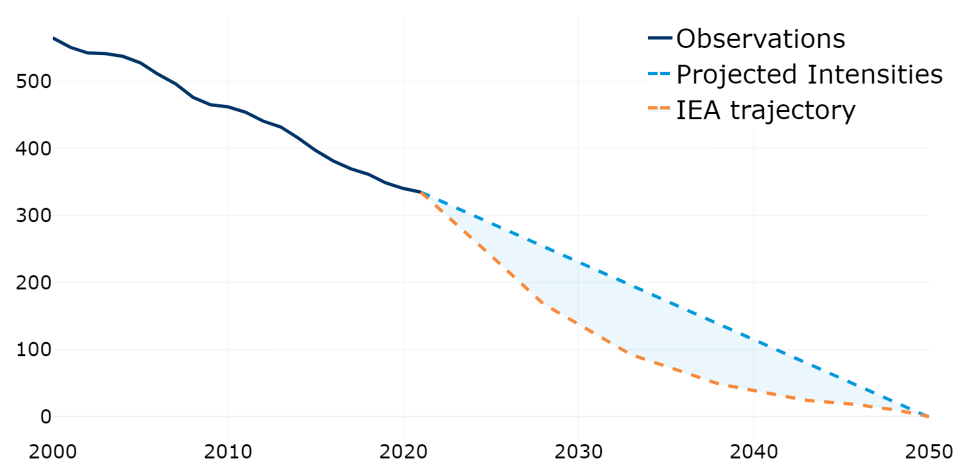
Figure 12: Contribution to the greenness of the Bloomberg Global Aggregate Treasuries by region



Source: World Bank, IEA and authors' calculations

Dealing with trends, if we look at the past carbon intensities of the current benchmark composition, we observe a clear reduction through time. However, those past efforts are not sufficient to limit global warming as agreed during the COP 15[1]. This is clearly shown on the following figure:

Figure 13: GHG emissions per GDP observed and projected intensities for the Bloomberg Global Aggregate Treasuries

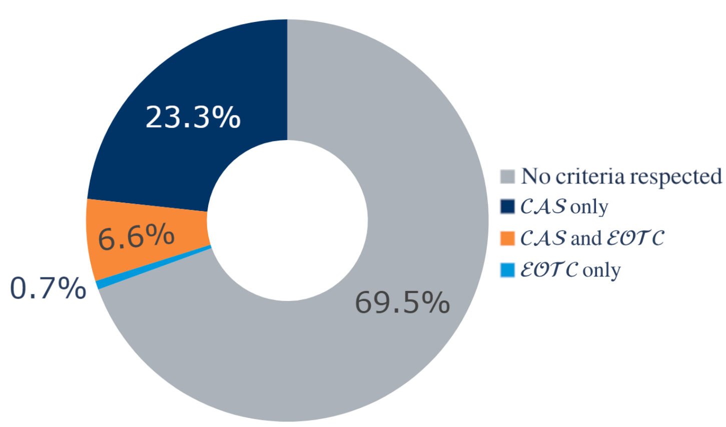


Source: IMF Climate Data, World Bank, IEA and authors' calculations

The light-blue area represents the difference in carbon budget between the linearly projected intensities and the corresponding IEA Net Zero trajectory. Here, even though both trajectories achieve net zero 2050, the IEA trajectory leads to a lower total carbon budget by 2050.

Moreover, NDC ambition and fulfilment metrics are insufficient in our initial portfolio as shown by Figure 14.

Figure 14: $\mathcal{CAS}$ and $\mathcal{EOTC}$ proportions in the Bloomberg Global Aggregate Treasuries



Source: IMF Climate Data, World Bank, IEA, UNFCCC and authors' calculations

[1] Conference of the Parties.

Indeed, only 6.6% of the portfolio belongs to a country which has an ambitious NDC ($\mathcal{EOTC}$ criteria) and whose carbon emissions are on track to achieve this NDC. 23.3% of the portfolio belongs to countries with commitment aligned with the scenario ($\mathcal{CAS}$ criteria), but are not on track to fulfil it. 69.5% of the portfolio is not on track to fulfil its NDC and has an unambitious NDC.

This analysis of the benchmark highlights the necessity to use rebalancing when considering sovereign portfolio alignment. Indeed, Figure 13 shows that projected emissions and intensities lead to a temperature rise over 1.5°C compared to pre-industrial levels. Indeed, the linear projection gives a carbon budget way greater than the one obtained by the IEA Net Zero trajectory. Even if all countries were to respect their NDCs, it would still lead to an increase of temperature of roughly 2.6°C. In addition, we observe thanks to Figure 14 that countries are more likely to satisfy the $\mathcal{CAS}$ criterion than the $\mathcal{EOTC}$ criterion. This can be interpreted as countries having ambitious targets but facing difficulties to meet these targets. This fact embodies the need for most countries to produce additional efforts in order to reach their pledges.

6 Results

In the following section, we ran some simulations to anticipate the behaviour of the net zero portfolio all along the decarbonisation trajectory. We update our portfolio by tracking our benchmark according to an objective function while fulfilling financial, decarbonisation and green constraints. The different simulations allow us to identify the best and worst candidates among countries when performing the alignment process, i.e. countries that will help to get a greener portfolio in line with a net zero scenario throughout the years. They also provide interesting information about financial risk that can arise when aligning a portfolio with a net zero trajectory.

Remark. In the following sections, we will use the misnomer of a net zero portfolio to refer to a portfolio aligned with a net zero trajectory.

6.1 Using spot carbon emissions

We need to formulate hypotheses about future carbon emissions to be able to simulate the behaviour of net zero portfolios. The simplest hypothesis that we can take is to consider the last picture of carbon emissions as a proxy. This scenario is equivalent to a "business as usual" (BAU) scenario, where each country keeps its GHG emissions the same as today.

6.1.1 Main net zero alignment process

We start by detailing the results of our main net zero alignment program which is the following:

$$x^\star = \underset{x}{\textbf{argmin}} \frac{1}{2}\sum_{i=1}^{n} |x_i - b_i| \quad \textbf{subject to} \quad x \in \mathbf{C_1}$$

This problem corresponds to an active share minimisation problems with the following constraints. It relates to the program ($\mathbf{P_1}$) described by the next table:

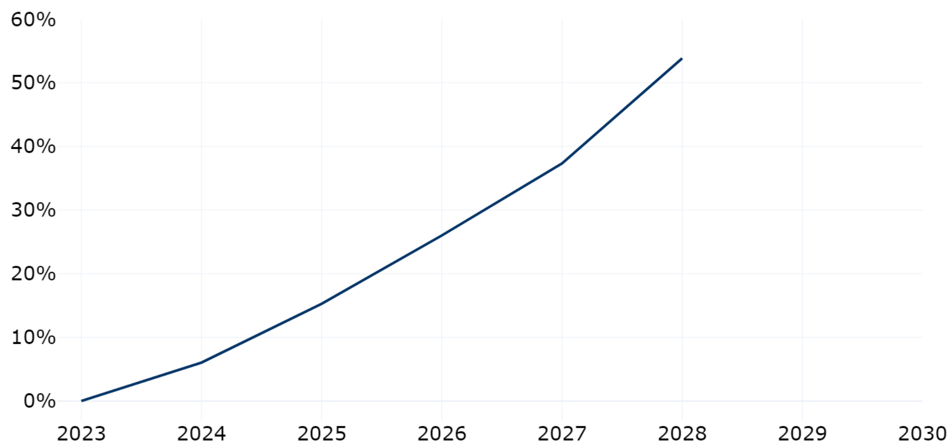
Table 8: Main net zero alignment problem - Table of constraints

Type	Name	Value
Weights	Long-only No leverage Min weight deviation by country Max weight deviation by country Proportion of advanced countries	✓ ✓ ✘ ✓ Within a 5% relative interval
Financial	Duration Ratings Yields	Same buckets Same buckets Within a 10% relative interval
Decarbonisation	$\frac{\text{GHG}}{\text{GDP}}$ intensity	IEA Net Zero Scenario[1]
Transition	Greenness Trend $\mathcal{CAS}$ [2] $\mathcal{EOTC}$ [3]	$\mathcal{G} = 0$ ✘ ✘ ✘

We chose greenhouse gas emissions per GDP as the carbon intensity for our problem as investors are more used to normalise by economic values. We opted for the IEA net zero scenario as our decarbonisation trajectory, mainly because it allows us to differentiate between emerging and developed countries. This scenario is also well-documented.

[1]We used the IEA Net Zero scenario expressed in tCO_2eq per million dollar of GDP.
[2]Commitments Aligned with the Scenario
[3]Emissions On Track with Commitments

Figure 15: Active share of the optimised portfolio (in %)



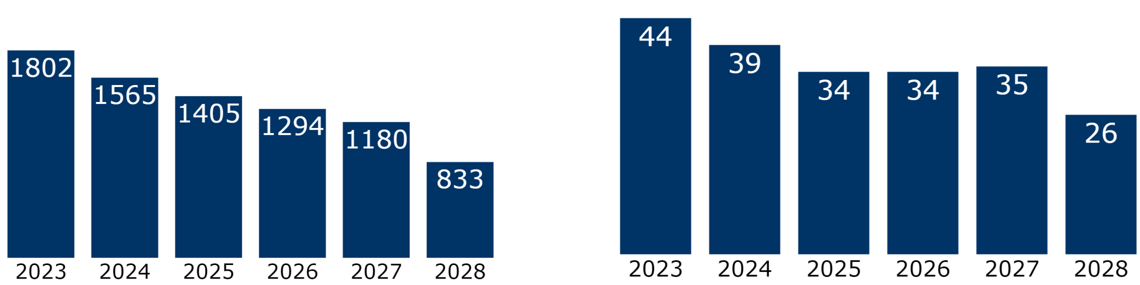
Source: IMF Climate Data, World Bank, IEA and authors' calculations

Figure 15 shows that the active share logically increases as decarbonisation trajectories become more binding. After 2028, no solution is found by the optimiser because constraints are too restrictive. The upper bound we impose on the carbon intensity and the maximum weight deviation are the main reasons for this absence of solutions. 2028 corresponds to an intensity reduction rate of roughly 36% for advanced countries and of 33% for emerging economies. We give the active share as a function of the carbon reduction rate if we assume the same reduction rate for advanced and emerging economies in Figure 42 in the appendix.

The results show that it will not be possible to build net zero portfolios with this investment universe after 2028, if the economy does not decarbonise faster in the near future. Of course, if countries make significant efforts, we would have to update our simulations to reassess the feasibility of net zero alignment. But knowing that current commitments are not sufficient enough to meet the Paris Agreement and that most countries are not on track with their NDC, it is very unlikely that the issuers in our investment universe will reach a sufficient level of decarbonisation to be net zero. Figure 15 also clearly shows that net zero alignment generates tracking risk, with the active share reaching more than 50% if countries do not reduce their carbon emissions.

Simulations show that net zero portfolio alignment also creates a concentration risk. Looking at the number of bonds through time shows us that the portfolio consolidates around fewer and fewer bonds and countries during the alignment process enlightening a concentration phenomenon:

Figure 16: Number of bonds and countries in the optimized portfolio by year



(a) Number of bonds (b) Number of countries

Source: IMF Climate Data, World Bank, IEA and authors' calculations

Yet, the concentration happens in a slightly different way for bonds and countries. Indeed, the number of bonds in the portfolio decreases almost linearly over the years. However, the number of countries decreases in a stepwise progression. This is due to the fact that carbon intensities are computed by country and therefore when the decarbonisation constraint becomes too expensive, the optimiser gets rid of countries with the worst carbon intensity/greenness profile. In the mean time, the optimiser is able to change the allocation of bonds issued by the same country without modifying the carbon intensity of the carbon portfolio. This allows the solver to respect financial constraints by getting rid of some securities in a linear way.

Table 9 gives the first exclusion year by country. As no solution is available from 2029, exclusion years[1] range from 2024 to 2029.

[1]i.e. the first year a country leaves the portfolio.

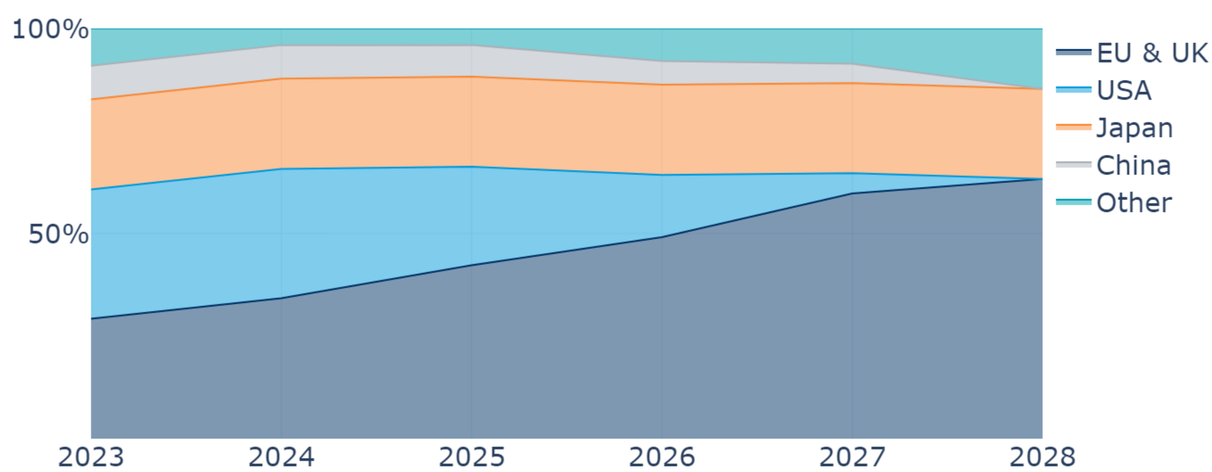
Table 9: First year out of the portfolio by country

Advanced eco.						Emerging eco.	
Australia	2025	Hong Kong	2029	New Zealand	2024	Chile	2029
Austria	2029	Ireland	2029	Portugal	2028	China	2028
Belgium	2028	Israel	2029	Singapore	2029	Colombia	2029
Canada	2024	Italy	2029	Slovakia	2025	Hungary	2029
Cyprus	2029	Japan	2029	Slovenia	2028	Indonesia	2024
Czechia	2024	Latvia	2028	South Korea	2024	Mexico	2029
Denmark	2029	Lithuania	2025	Spain	2028	Malaysia	2028
Estonia	2025	Luxembourg	2029	Switzerland	2029	Peru	2029
Finland	2029	Malta	2029	Sweden	2029	Poland	2029
France	2029	Netherlands	2029	United Kingdom	2029	Romania	2029
Germany	2029	Norway	2029	United States	2028	Thailand	2025

Source: IMF Climate Data, World Bank, IEA and authors' calculations

Five countries disappear from the portfolio the first year: Canada, Czechia, South Korea, Indonesia and New Zealand. In the last portfolio in 2028, 7 emerging countries out of 11 and 19 advanced economies out of 33 remain. It is worth noting the disappearance of the United States in 2027 and China in 2028. 11 countries have unchanged weights all along the problem. The full table of weights is available in Table 18 in the appendix. The next figure shows the evolution of weights by region.

Figure 17: Weights' evolution in the optimised portfolio by region



Source: IMF Climate Data, World Bank, IEA and authors' calculations

Japan's weight in the portfolio remains constant all along the alignment process. In the mean time, China and the USA progressively disappear, mainly in favour of the EU and the United Kingdom. A large majority (over 65%) of the final portfolio is constituted by Western European countries, with principally the United Kingdom (17.8%), Ireland (6.4%), France (5.4%), Switzerland (5.0%) and Denmark (4.7%).

Duration and ratings are constrained to keep the same bucket breakdown than the initial portfolio. Constraining the yield to maturity to vary of 10% at most is not costly. Indeed, we do not reach any of the lower and upper bounds with regards to the yield constraint. This is shown by the following table as the lower bound and upper bounds are respectively 3.65% and 4.46%.

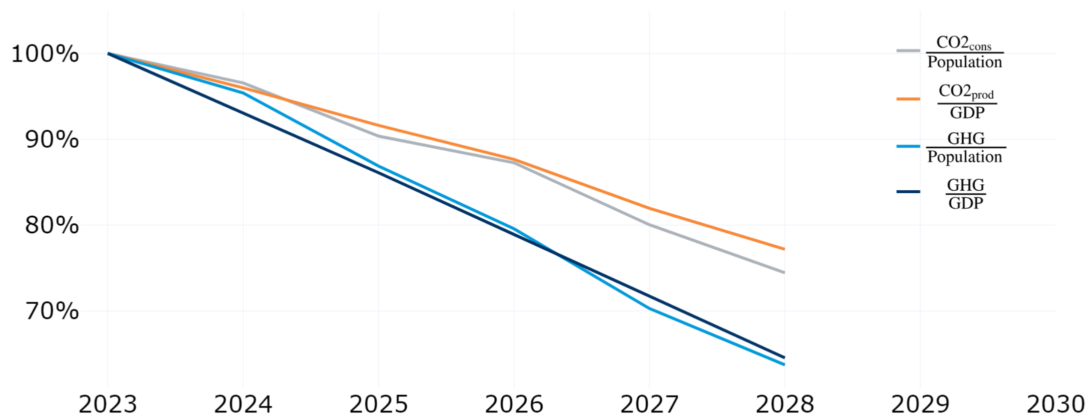
Table 10: Yields by year

Year	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**
Yields	4.05%	3.98%	3.96%	3.91%	3.88%	4.29%

Source: Bloomberg, IMF Climate Data, World Bank, IEA and authors' calculations

Figure 18 depicts the evolution of carbon intensities alongside the alignment process. In our case, all carbon intensities are decreasing almost linearly but at different rates. For example, reducing greenhouse gas emissions per GDP by 35% in 2028 results in a reduction of CO_2 from production per GDP by only 23%. Consequently, decarbonising by setting constraints on one variable does not imply that the other parameters also respect the defined scenario. If we want all intensities to respect the scenarios, we have to impose constraints on each of them.

Figure 18: Evolution of the relative carbon intensities in the optimised portfolio



Source: IMF Climate Data, World Bank, IEA and authors' calculations

Taking a deeper look, we notice a clear shift in the contribution to carbon intensities by region. This is shown by Figure 19:

Figure 19: Contribution to the carbon intensity

(a) Distribution in 2023 (b) Distribution in 2028

Source: IMF Climate Data, World Bank, IEA and authors' calculations

Initially, the US and China contribute to over 50 % of the carbon intensity of our portfolio. The remaining 48% is almost evenly shared by the three other groups (the EU and the UK, Japan and Other). However, as China and the US progressively disappear from the portfolio, we end up having a 2:1:1 ratio with a prevalence by the the EU and the UK group.

Looking at the contribution to greenness clearly shows the overwhelming importance of the European Union and the United Kingdom in the final portfolio greenness.

Figure 20: Contribution to the greenness

(a) Distribution in 2023 (b) Distribution in 2028

Source: IMF Climate Data, World Bank, IEA and authors' calculations

It is also interesting to note that despite being responsible for 36% of the greenness of the initial portfolio, the United States is removed from the net zero portfolio in 2028 due to its poor carbon metrics. At first sight, it may seem that the greenness constraint drives the over-weighting of the EU and the UK in the optimised portfolios. However, it is mostly the result of the decarbonisation constraints. Even without the greenness constraint, we obtain the same distribution of contributions to greenness by region.

We can also have a look at the greenness dynamics alongside the alignment process. Table 11 shows this evolution relatively to the benchmark. It also features the evolution of the greenness between advanced and emerging economies.

Table 11: Greenness evolution relatively to the benchmark alongside the alignment process

	2023	**2024**	**2025**	**2026**	**2027**	**2028**
All Countries	100.00%	100.00%	100.00%	110.85%	125.82%	129.68%
Advanced economies	100.00%	99.99%	99.96%	111.42%	126.92%	126.75%
Emerging economies	100.00%	100.37%	101.88%	84.87%	75.21%	263.91%

We first observe that the greenness increases significantly in the last years. The constraint we set on the greenness is mainly useful in 2024 and 2025 as we remain on the allowed lower bound. The huge greenness rise that occurs the last year for emerging economies is mainly due to a concentration effect on Poland, Peru and Hungary with a respective increase of 3.55%, 2.90% and 1.93% between the last two years. However, the portfolio's greenness is almost always conditioned by the greenness of advanced economies. In 2028, they contribute to almost 98% of the greenness.

As carbon intensities are constrained in this problem but not the carbon trend, it is interesting to analyse the natural evolution of the carbon trend along the alignment process. The following table presents the trend of the greenhouse gas emissions per GDP as it is the constrained carbon intensity. We observe that as this intensity decreases, its normalised trend slightly increases, meaning that the overall dynamic of carbon reduction has been deteriorated.

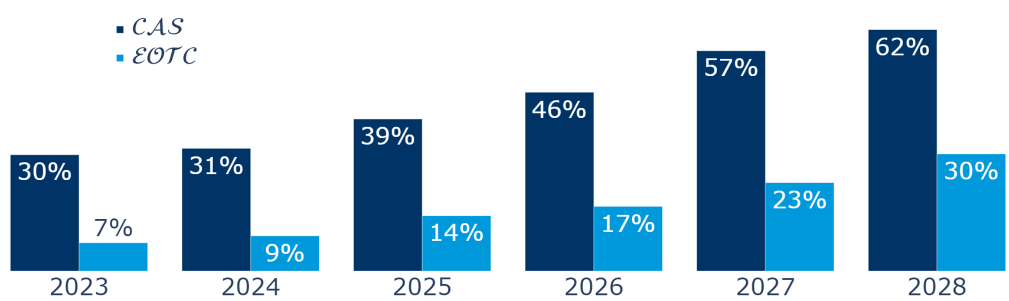
Table 12: Trends in carbon intensity of the optimised portfolio

	Trends	**Normalised trends**
2023	-11.58	-3.46%
2024	-11.12	-3.43%
2025	-10.41	-3.24%
2026	-9.24	-2.79%
2027	-8.75	-2.75%
2028	-7.82	-2.44%

Source: IMF Climate Data, World Bank, IEA and authors' calculations

However, carbon trends alone are not sufficient to analyse the future dynamic of carbon emissions. It is worth assessing how countries' commitments[1] behave compared to historical trends. To do so, we track the two metrics dealing with NDCs we defined previously. We start by checking every year the weight percentage of the portfolio that respects the $\mathcal{CAS}$ criterion[2]. Then, we check if countries' historical trends are in line with their commitments according to the $\mathcal{EOTC}$ criteria. To measure it, we allowed a tolerance rate of 10% to simulate the potential tendency of countries to realign their trend of emissions in order to meet their NDC's pledge[3]. Figure 21 depicts the evolution of the proportion of these two measures.

Figure 21: Weight percentage in the optimised portfolio respecting the $\mathcal{CAS}$ and $\mathcal{EOTC}$ criteria



Source: IMF Climate Data, World Bank, IEA, UNFCCC and authors' calculations

Both proportions increase significantly overtime. However, we are far from achieving a portfolio that is fully on track with the IEA NZ scenario requirements to limit temperature rise to 1.5°C as we have 62% and 30% respecting the $\mathcal{CAS}$ and $\mathcal{EOTC}$ criteria in 2028. All the countries that meet the $\mathcal{EOTC}$ criterion also respect the $\mathcal{CAS}$ criterion. In addition, we observe that naturally countries are more likely to satisfy the $\mathcal{CAS}$ criterion than the $\mathcal{EOTC}$ criterion. That indicates countries often have more ambitious targets than historical projections on track with these targets. This means that most of them are still far from meeting the emission target they set in their NDC. An interesting fact that stands out from this first analysis of the main problem is that we are globally working within a coherent framework. Constraining only our portfolio to decarbonise without losing its greenness leads to an overall increase of both the greenness and the part of the portfolio respecting the $\mathcal{CAS}$ and $\mathcal{EOTC}$ criteria.

6.1.2 Problem's sensitivity to the current constraints

Before increasing the complexity of the problem by adding other net zero constraints, it is important to look at the sensitivity of the results when varying some parameters of the initial set of constraints. In this section, we assess the marginal impact of removing some constraint or modifying their magnitude in terms of tracking risk and portfolio composition.

Removing maximum weight deviation constraints

This part aims at showing the need to impose maximum deviation constraints when dealing with sovereign portfolio alignment. Indeed, let us consider an optimisation problem similar to our main optimisation problem but without maximum deviation constraints. The whole set of constraints is specified in Table 19 in the appendix.

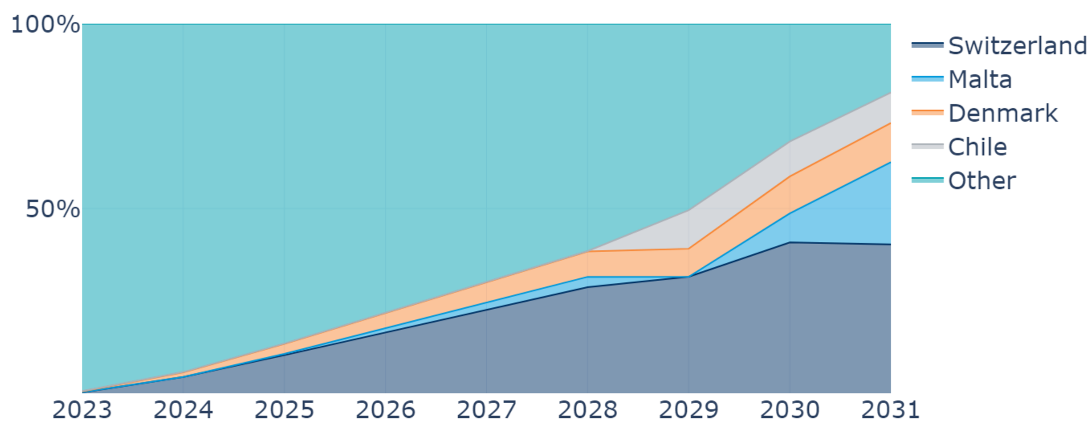
First, getting rid of maximum deviation constraints allows the optimiser to find solutions to the alignment problem until 2031, three years later than the main problem. Obviously, as we impose less control on this

[1] Currently made in 2030 in the NDCs.
[2] Defined in Table 4.2.4.
[3] That is to say countries whose projected emissions in 2030 are 10% over their NDC target are still considered on track.

problem, its active share is lower than the active share of the original problem on the comparative period. As a matter of fact, it induces an absolute difference of around 15% in 2028. Figure 43 in the appendix depicts the difference in active share between the two problems. We also compare the number of bonds and countries in Figure 44 Appendix *C*.2.

However, this gain in active share comes at a certain cost. Figure 22 shows the evolution of the four largest countries[1] compared to the others. Without maximum deviation constraints, we see that Switzerland, Malta, Denmark and Chile that constituted less than 0.6% of the original portfolio end up making over 80% of the final portfolio. Switzerland alone constitutes over 40% of the portfolio in 2031 while Malta's weight is being multiplied by over 10,000 compared to the benchmark. Table 20, comparing the weights in the last obtained portfolio for the main net zero problem with and without maximum deviation is available in the appendix.

Figure 22: Weights' evolution without deviation constraints



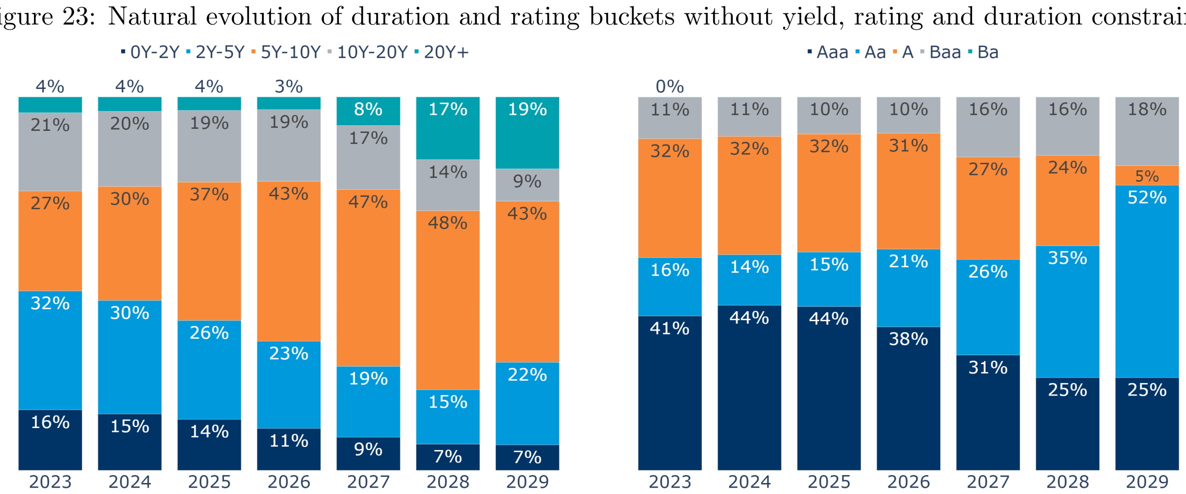
Source: Authors' calculations

It is thus clear that it is mandatory to impose maximum deviation constraints while building net zero alignment optimisation problems. Otherwise, obtained portfolios are unrealistic for investors.

Importance of duration, rating and yield constraints

As previously stated, keeping important financial characteristics of the benchmark when aligning a portfolio is an important requirement for asset owners and asset managers. Therefore, we can investigate the cost of such constraints. The first thing to notice is that suppressing these financial constraints allows the optimiser to find a solution in 2029, that is to say one year after the main problem. Figure 23 shows how buckets of ratings and duration evolve if they are not constrained in the problem.

Figure 23: Natural evolution of duration and rating buckets without yield, rating and duration constraints



(a) Evolution of duration buckets (b) Evolution of rating buckets

Source: Bloomberg, IMF Climate Data, World Bank, IEA and authors' calculations

The graph on the left shows that duration buckets vary in two ways. First, the proportion of bonds that have medium and long duration (i.e. $5Y+$) increases over time to the detriment of bonds with lower duration. In the mean time, within bonds with long duration, the proportion of 10 to 20 year bonds diminishes. The graph on the right highlights that rating buckets seem to be quite stable until 2028. In particular, the split Aaa vs Aa drastically changes as of 2028 with Aa rated bonds constituting over half the portfolio the last year. This is due to the overweight of European advanced economies in the portfolio at the end. It is mainly A rated Chinese and Japanese bonds as well as Aaa rated American bonds that are traded in favour of Aa rated bonds. Thus, the rating evolution would not be a concern for many investors as it tend to improve over time in our case.

[1] In terms of weights in 2031.

Concerning the yield to maturity, it is quite stable until the last year as it remains in a ±10% relative interval[1]. An interesting observation is that for the Bloomberg Global Aggregate Treasuries and our main net zero problem, only the constraints on ratings have a significant effect on the active share. To see that, we generate eight variants of the main problem. The set of constraint of each of these problems is defined by adding or removing duration, yield and rating constraints to the main problem. For a given problem, we sum the difference in active share compared to the original problem between 2023 and 2028. The following table sums up the results. Cells with a ✓sign indicate that the problem in the corresponding column contains the constraint named at the cell's row.

Table 13: Differences (as sum of active shares in %) compared to the main net zero alignment problem

Duration constraints	✓				✘			
Yield constraints	✓		✘		✓		✘	
Rating constraints	✓	✘	✓	✘	✓	✘	✓	✘
Active share delta	0.00%	-5.06%	0.00%	-5.06%	0.00%	-5.06%	0.00%	-5.06%

Source: IMF Climate Data, World Bank, IEA and authors' calculations

Even though in the unconstrained problem duration buckets seem to be unstable, the cost of maintaining similar buckets is lower than the one required to maintain similar rating buckets. Likewise, keeping the average yield in a specific interval is not expensive at all in terms of active share.

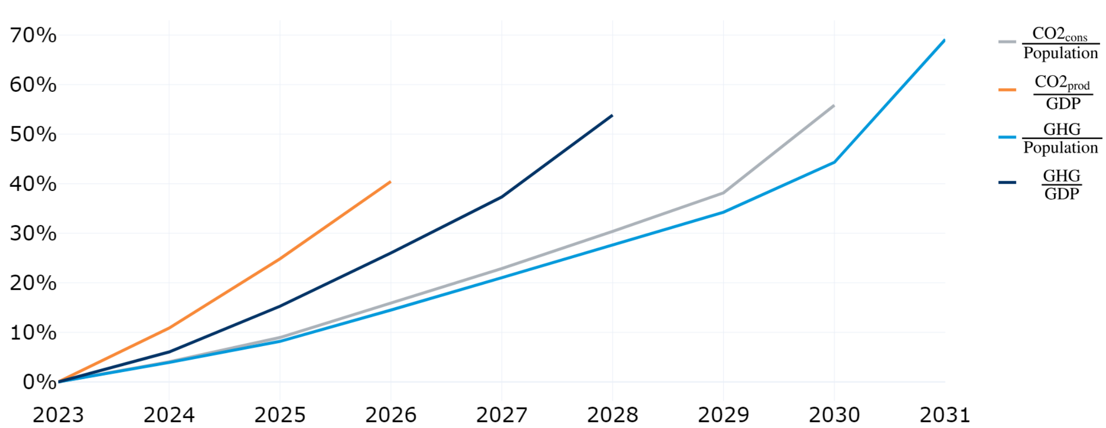
Constraining only advanced (resp. emerging) economies to decarbonise

Some investors may be interested to decarbonise only advanced or emerging economies in their portfolio. In the following part, we keep the same constraints as in our main net zero alignment problem except for the decarbonisation constraints. In our case, if we only constrain advanced economies to decarbonise, there are no more solution after 2028 with a last reached active share of 39.5%. Similarly, if we only constrain emerging economies to decarbonise, the last active share obtained is 12.9% in 2035. The large difference in active share obtained between these two symmetric cases is due to the fact that advanced economies constitute most of the benchmark (initial portfolio) weights. In both cases, the unconstrained category quickly reaches its maximum allowed upper bound, i.e. 92.5% for advanced economies and 17.3% for emerging economies as we set the weight by development level to deviate from its base value of 5% at most. Figure 46 in the appendix shows the weight evolution of the top 5 advanced and emerging countries in the benchmark in both cases. We observe that when only constraining emerging economies, advanced economies' weights remain almost the same while the symmetric scenario happens when constraining only advanced economies.

The impact of carbon intensity metric

In this paragraph, we try to analyse the impact of choosing a different carbon intensity metric to constrain in our alignment process[2]. As shown in section 3.1, carbon accounting choices are fundamental and may imply very different bias. The idea is thus to run simulations keeping the same constraints as the main net zero alignment problem but modifying the carbon intensity metric. Depending on the intensity used, we obtain the following active shares:

Figure 24: Active share comparison based on the intensity used



Source: IMF Climate Data, World Bank, IEA, Bloomberg and authors' calculations

The theoretical final year ranges from 2026 to 2031 depending on the carbon accounting. In all cases, the active share is not linear and we notice a leap that starts on the second to last year. Consumption-based intensities lead to more solutions than production-based intensities. They also generate less tracking risk. Indeed, this is due to a wider distribution of intensities per capita, as shown in section 3.1.2. Wider distributions make it easier to find solutions to decarbonise the portfolio, removing the worst emitters and over-weighting the best. Moreover, when we adopt a consumption-based point of view, emerging economies seem to be favoured, meaning that their carbon intensities tend to be lower than advanced economies. However, when we adopt a production-based metric, advanced economies are preferred to emerging countries, probably due to different industry breakdown and more carbon efficient processes. The constraints we imposed on weight deviation prevent the optimiser from selecting a large part of the portfolio in bonds

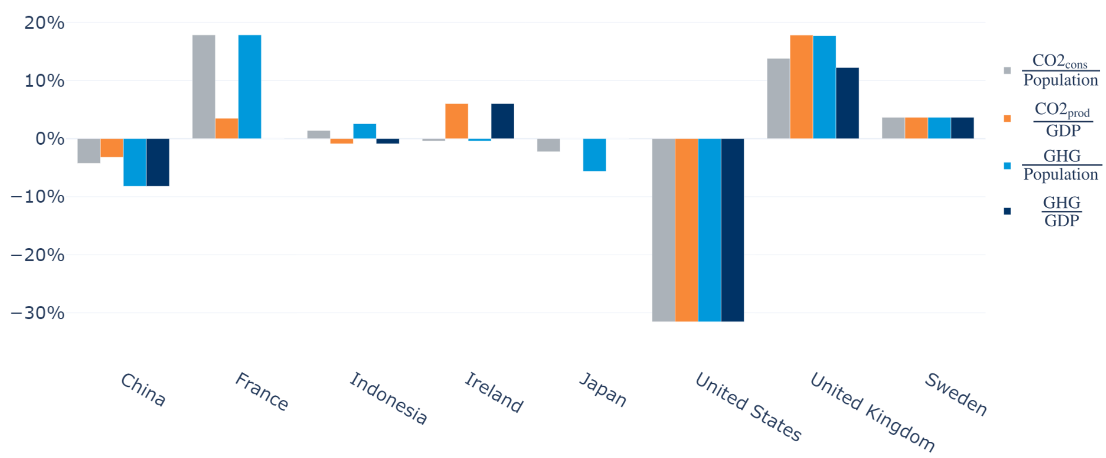
[1] Figure 45 in the appendix compares the yield evolution for the main problem with and without duration, rating and yield constraints.

[2] This corresponds to the set of constraints presented in Table 23 in the appendix.

from emerging countries. Thus, problems in emissions per GDP, for which emerging countries have a higher intensity, end up earlier than problems in emissions over population.

It is also worth noting that the weight allocation by country can substantially differ between different intensities. We give hereafter a few examples of the weights obtained by country on the last obtained year by problem relatively to the initial portfolio[1].

Figure 25: Weight deviation from the benchmark based on the intensity used for the last obtained portfolio



Source: IMF Climate Data, World Bank, IEA and authors' calculations

Figure 25 shows the absence of pattern in this weight variation. For instance, Sweden always reaches its maximum allowed deviation. Ireland achieves its upper weight bound only in problems using emissions per GDP. Indonesia's weight in the portfolio increases in consumption-based intensities but decreases[2] in production-based GDP. Not only are weights distributed variously but countries leave the portfolio at distinct dates according to the intensity we use. This is featured by Table 14[3].

Table 14: Exclusion year by country by intensity type

	$\frac{CO2_{cons}}{Population}$	$\frac{GHG}{Population}$	$\frac{CO2_{prod}}{GDP}$	$\frac{GHG}{GDP}$
China	2031	2031	2027	2028
France	2031	2032	2027	2029
Indonesia	2031	2032	2024	2024
Ireland	2030	2030	2027	2029
Japan	2031	2032	2027	2029
USA	2029	2030	2026	2028
UK	2031	2032	2027	2029
Sweden	2031	2032	2027	2029

Source: IMF Climate Data, World Bank, IEA and authors' calculations

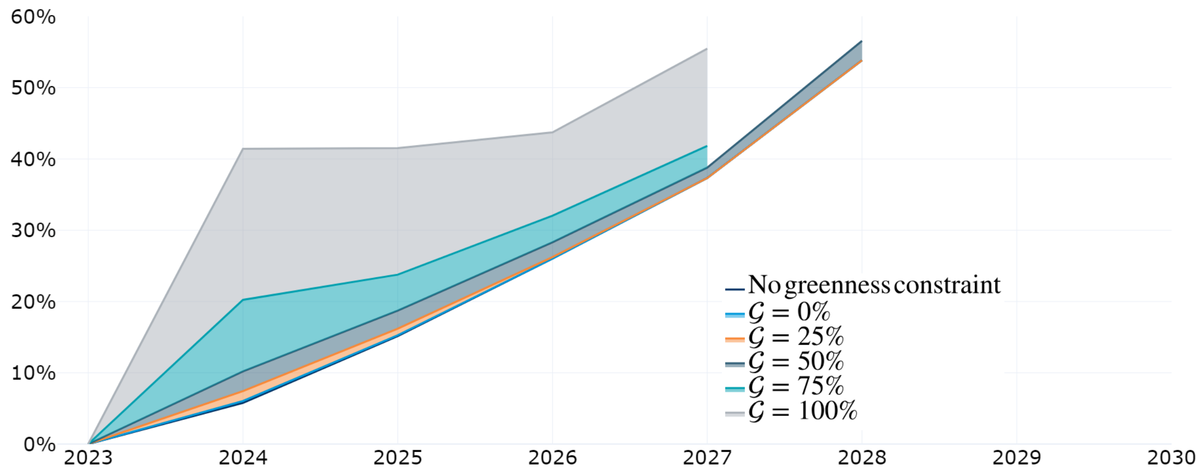
For a country like Indonesia, there is a clear gap between its year out of the portfolio when considering emissions per capita (2030+) or per GDP (2024). Some other countries like France always end up in the final portfolio with a non-negative difference with its original weight.

Greenness constraints

So far, we have only set the greenness of the optimised portfolio to be at least greater than the benchmark's. But it is interesting to go a bit further and see the effect of the greenness coefficient on the portfolio obtained. Requiring the optimised portfolio's greenness to be greater than the benchmark's greenness represents a relatively negligible cost in terms of active share. However, increasing the greenness becomes more and more costly as the greenness growth factor $\mathcal{G}$[4] rises. Figure 26 features the marginal contribution of the greenness constraint as a function of the greenness growth factor $\mathcal{G}$.

[1] The full weight table comparison is given by Table 25 in the appendix.
[2] It even reaches 0 leading to the disappearance of Indonesia in the portfolio.
[3] The complete table can be found in the appendix. (See Table 24).
[4] We recall that it corresponds to a greenness of the optimised portfolio greater than $(1 + \mathcal{G})$ times the benchmark's.

Figure 26: Impact of the greenness growth factor $\mathcal{G}$ on the active share of the optimised portfolio



Source: IMF Climate Data, World Bank, IEA and authors' calculations

Increasing the greenness is especially expensive when we require a gain over 75%. Keeping an increase of at least 50% induces at most a 4.2% difference in active share when setting this increase to 75% leads to a maximum of 14.2% difference in active share. Doubling the greenness becomes even more costly as it involves a 35% difference in active share in 2024 compared to the original problem. These results show that the additional cost of implementing a net zero policy also concerns a short-term horizon and is all the more expensive at the beginning of the process than at the end[1]. This implies a noticeable difference of the alignment process whether we only consider the decarbonisation dimension or we also add a transition dimension.

6.1.3 Addition of other net zero metrics

In order to have an optimization problem in line with the four pillars of our definition of net zero described in section 1, we introduce a new set of constraints, mostly concerning dynamic and forward-looking metrics.

Adding normalized trends

To further implement the transition dimension in our portfolio, we take a look at trends' constraints. One of the first ideas in order to favour diminishing carbon emissions is to exclude countries with trends above a certain value $\mathcal{CN}^{max}$. This translates into the following implication for each country j:

$$\mathcal{CN}_j \geq \mathcal{CN}^{max} \Rightarrow w_j = 0$$

where w_j designates the weight of country j in the portfolio. Referring to Table 13, it might seem reasonable to set $\mathcal{CN}^{max}$ to 0 in order to exclude all countries with increasing emissions. However, this can be challenging as we count only 44 countries in our portfolio. This constraint is in fact unimplementable for many asset owners and managers. Unlike companies in equity portfolios, excluding even a small number of countries in a sovereign bond portfolio leads to an optimisation problem that is way harder. As a matter of fact, in our case, it prevents the solver from finding a solution even on the first year.

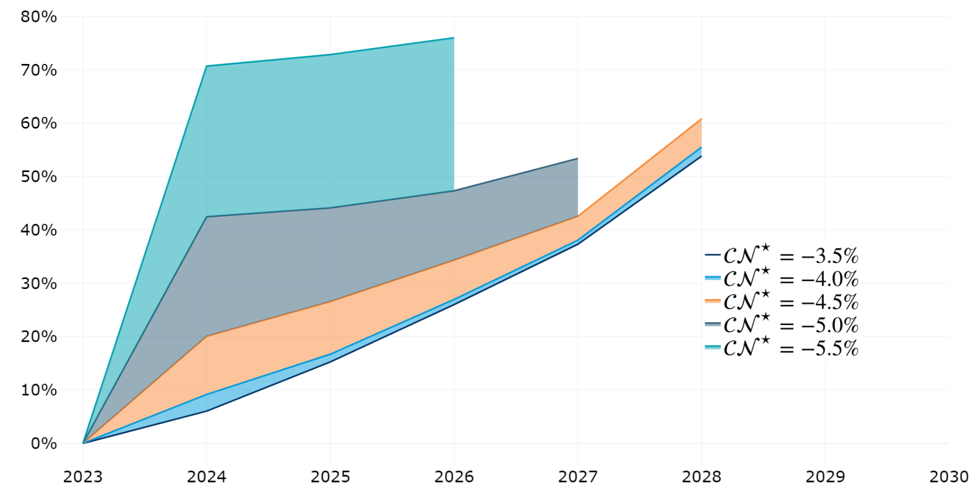
Therefore, we have to explore other ways of incorporating the carbon trend. As we selected an intensity expressed in GHG emissions per GDP to decarbonise our portfolio, we also considered trends in emissions per GDP to foster self-decarbonisation. We recall from Table 12 that our benchmark's normalised trend is roughly -3.46%. We investigated the effect of imposing different values of $\mathcal{CN}^{\star}$ in terms of tracking risk:

$$\mathcal{CN}(x) \leq \mathcal{CN}^{\star}$$

Figure 27 gives the evolution of the active share through time given different carbon trends thresholds values:

[1] As shown by the spike directly at the beginning of the first period.

Figure 27: Impact of $\mathcal{CN}^\star$ on the active share of the optimised portfolio



Source: IMF Climate Data, World Bank, IEA and authors' calculations

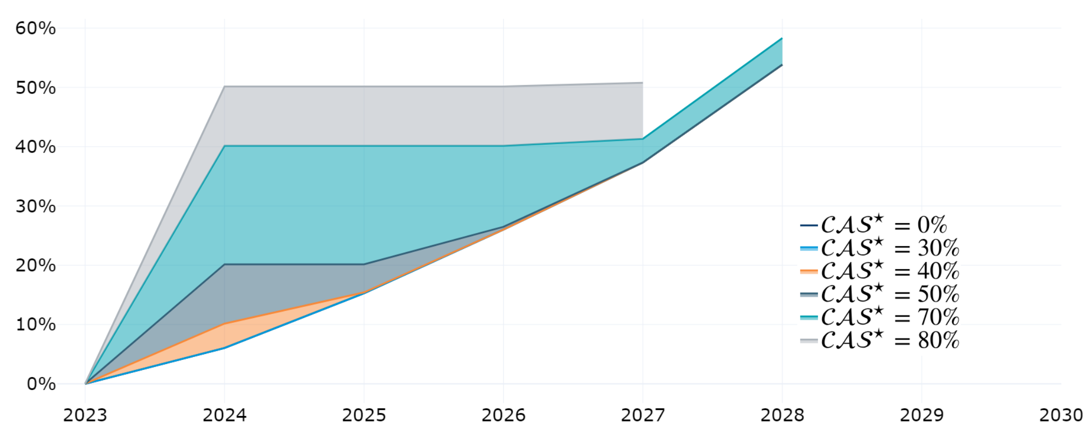
It is quite easy for the optimiser to satisfy the constraints without increasing too much the active share compared to the main net zero alignment problem for values of $\mathcal{CN}^\star$ close to the benchmark's normalised trend[1]. However, if we try to reach smaller and smaller trends, the initial cost in active share is huge (around 65%). But, once this step has been overcome, there is only a slight increase in active share for the following years. The optimiser cannot find solutions[2] when $\mathcal{CN}^\star$ falls below roughly -5.6%.

Adding forward-looking measures

Finally, we use constraints in relation to NDCs in order to implement forward-looking measure, as introduced in section 4. Just like for trends, excluding countries with unambitious commitments (based on the $\mathcal{CAS}$ measure[3]) or countries which are not on track to fulfil their NDC (based on the $\mathcal{EOTC}$ measure[4]) is really difficult as we only have 44 different countries in our portfolio.

Again, to bypass this issue, we can use several types of requirements: beating the benchmark, increasing along a trajectory over time, targeting a certain proportion in the portfolio, etc. Here we chose to vary the proportion of countries whose commitments are aligned with the IEA net zero scenario (resp. on track with their NDCs) to be at least $\mathcal{CAS}^\star$ (resp. $\mathcal{EOTC}^\star$). Figure 47 in the appendix features the number of countries[5] respecting the $\mathcal{CAS}$ (resp. $\mathcal{EOTC}$) criteria as a function of the tolerance rate we allow. The following figure depicts the marginal increase in active share compared to our main net zero alignment problem depending on $\mathcal{CAS}^\star$:

Figure 28: Impact of $\mathcal{CAS}^\star$ on the active share of the optimised portfolio

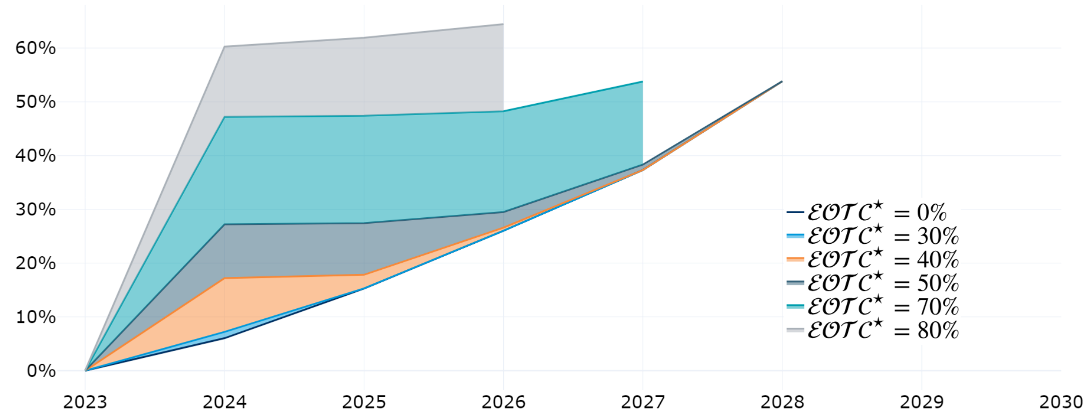


Source: IMF Climate Data, World Bank, IEA, UNFCCC and authors' calculations

Once again, we observe a jump in active share at year one, and then a threshold effect. Constraint on $\mathcal{EOTC}^\star$ has a similar profile but generates even more tracking risk:

[1] Which is roughly -3.6%.
[2] Even the first year.
[3] Commitments aligned with the Scenario (see section 4.2.4).
[4] Emissions on track with the commitment (see section 4.2.4).
[5] Out of the 44 countries initially present in the Bloomberg Global Aggregate Treasuries.

Figure 29: Impact of $\mathcal{EOTC}^\star$ on the active share of the optimised portfolio



Source: IMF Climate Data, World Bank, IEA, UNFCCC and authors' calculations

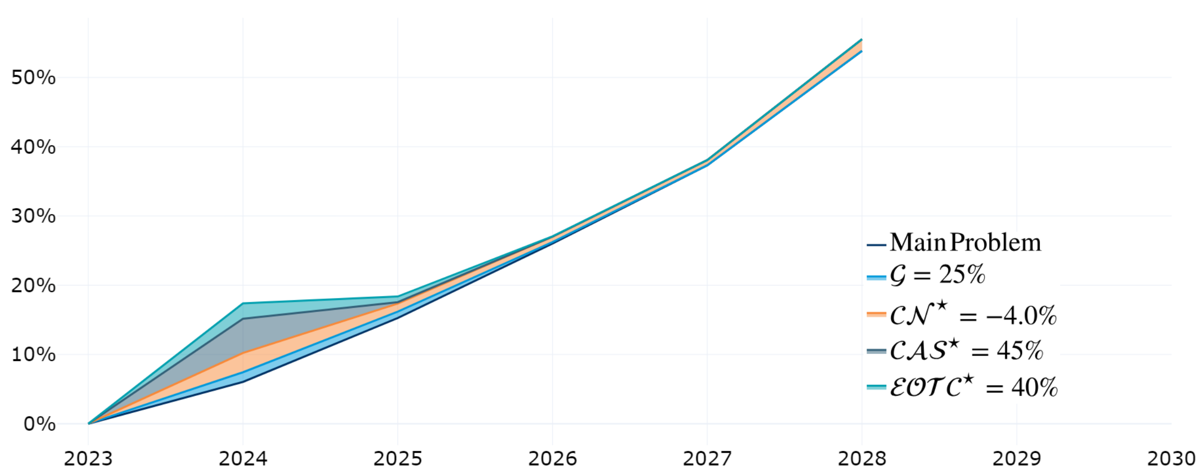
Once again, the increase in active share is neither a linear function of $\mathcal{CAS}^\star$ nor $\mathcal{EOTC}^\star$. Indeed, we have some quick wins at the beginning that allow us to meet the requirements without losing too much active share. However, when we want to have higher proportions, i.e. over 70%, the additional change in active share becomes really costly. The optimiser is unable to find solutions for $\mathcal{CAS}^\star = 86\%$ and $\mathcal{EOTC}^\star = 81\%$. For now, it seems very complicated to obtain a portfolio that fully respects both $\mathcal{CAS}^\star$ and $\mathcal{EOTC}^\star$ criteria. Dealing with including the $\mathcal{EOTC}$ criteria in our set of constraints, we can adopt another outlook to assess whether the portfolio is on line with countries' commitments. In fact, we could define a portfolio commitment which would represent the emission target that should be reached by the portfolio in 2030 based on countries' NDCs' aims. We can then evaluate how far the portfolio is from achieving this target and constrain it to attain this objective.

6.1.4 Aggregation of all the constraints

In the previous section, we assessed the marginal effect of modifying the magnitude of each constraint solely. We now complexify the net zero alignment problem step by step to integrate all the dimensions at the same time. Indeed, aggregating all the previously seen constraints[1] allows us to see the marginal contribution in active share of each constraint successively. It is important to note that results are sensitive to the chosen order of constraints. That is why we have ordered the constraints from the most to the least common.

We start by providing an example with modest constraints. In addition to the main problem, we successively require the greenness to be 50% higher than the benchmark, the normalised trend to be below -4%, the $\mathcal{CAS}$ and $\mathcal{EOTC}$ proportions to be respectively at least 45% and 40%.

Figure 30: Marginal contribution of each net zero constraint to additional active share

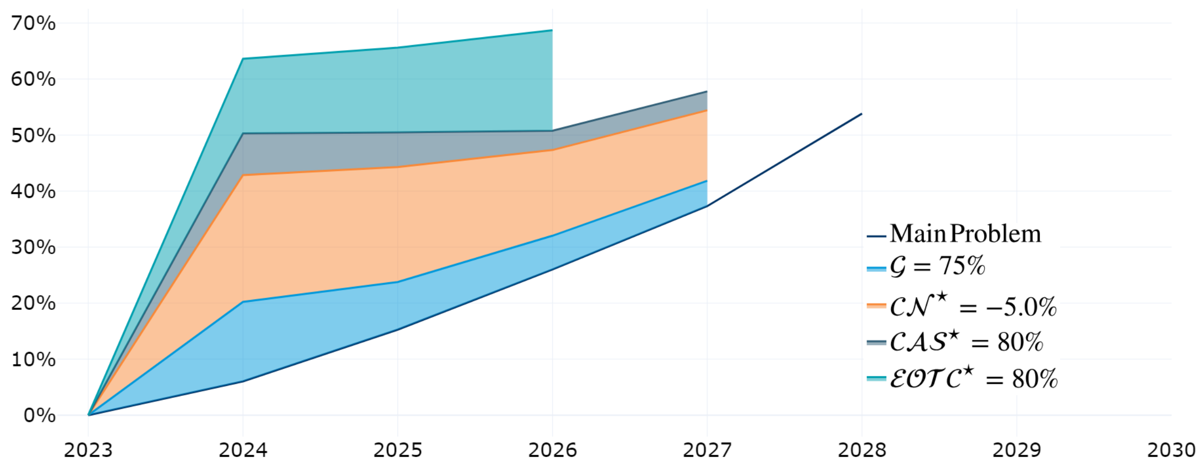


Source: IMF Climate Data, World Bank, IEA, UNFCCC and authors' calculations

As expected, we are able to find a solution every year between 2023 and 2028 for all problems and every constraint leads to a small initial increase in active share. However, this initial growth does not last and from 2026, the discrepancy in active share between the most constrained and the original problem is barely visible. If we had to set lower parameters, all the constraints would have been almost immediately granted with no perceptible rise in active share. We can compare the previous graph to a case where we set highly restrictive constraints with a greenness that is 1.75 times the benchmark's, a normalised trend of -5.0%, $\mathcal{CAS}^\star = 80\%$ and $\mathcal{EOTC}^\star = 80\%$.

[1] We successively add the constraints going from the main problem to the problem described by Table 26.

Figure 31: Marginal contribution of each net zero constraint to additional active share



Source: IMF Climate Data, World Bank, IEA, UNFCCC and authors' calculations

In this case, the increase in active share is much more visible especially the first year with an increase of 58% between the main problem and the most constrained problem. Moreover, this increase only slightly diminishes over time where it used to be invisible in the previous situation (Figure 30). This is all the more true when we add the constraint on normalised trend. In addition, the optimiser last finds a solution between 2026 and 2028 depending on the problem.

The two examples above give very different pictures of constraint's overlap, highlighting the importance of simulations.

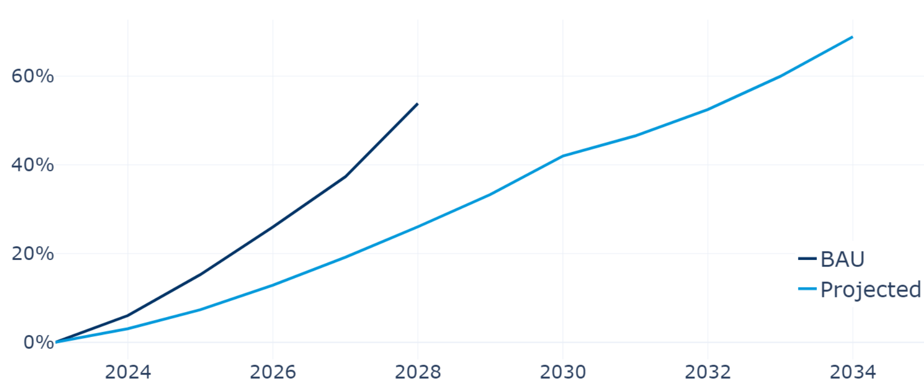
6.2 Using projected carbon emissions

In the last section, we used a "business as usual" hypothesis to simulate the behaviour of net zero portfolios in the future. But this scenario can be seen as too pessimistic, as most countries display downward sloping carbon emissions. An other possible approach would be to consider projected carbon emissions as a proxy of future carbon emissions. It simulates the behaviour of net zero portfolios in a scenario where each country pursues its past efforts. For the following computations and examples, we used linear projections based on historical observations, with a floor.

6.2.1 Main net zero alignment process

To compare to the BAU[1] scenario, we optimise exactly the same main net zero alignment problem, but considering projected emissions instead of last available carbon emissions[2]. This adjustment allows the optimiser to find solutions until 2034. This also leads to a significant difference in active share. We compare the previous active share with the new one in Figure 32.

Figure 32: Active share comparison - BAU vs. Projected emissions



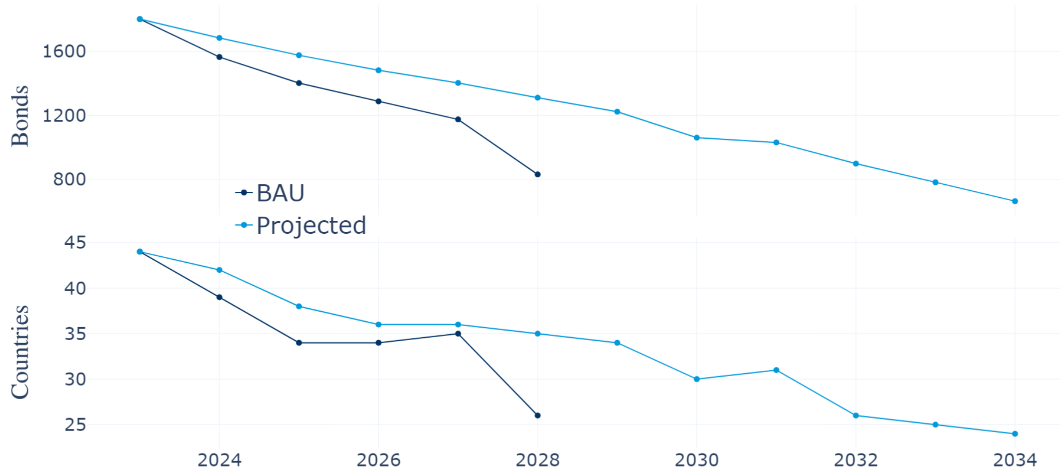
Source: IMF Climate Data, World Bank, IEA and authors' calculations

We observe an active share win of 28% in 2028 if we suppose that each country pursues its past efforts. Thus, simulations using projected emissions suggest a lower tracking risk.

We draw a similar conclusion on concentration risk. The numbers of bonds and countries have a similar behaviour with both carbon intensity metrics. In 2028, we have more bonds and countries that remain in the optimised portfolio in the projected emissions case. But we reach a final number of bonds and countries in the last optimised portfolio that is slightly lower than what was obtained in the BAU case, but six years later. This phenomenon is well illustrated on the following figures:

[1] Business As Usual.
[2] That corresponds to the set of constraints described by Table 27 in the appendix.

Figure 33: Number of bonds and countries - BAU vs. Projected emissions



Source: IMF Climate Data, World Bank, IEA and authors' calculations

To take a closer look, Table 15 compares the evolution of the weight allocation and the exclusion year by country[1] between the BAU and the projected scenario.

Table 15: Simplified weight table by country - BAU vs Projected emissions

	BAU			Projected emissions		
	2023	**2028**	**Year Out**	**2028**	**2034**	**Year Out**
Advanced economies	88.14 %	85.44 %		88.13 %	85.33 %	
Canada	1.74 %	0.00 %	2024	0.00 %	0.00 %	2025
Czechia	0.27 %	0.00 %	2024	0.00 %	0.00 %	2024
Denmark	0.22 %	4.66 %	2029	4.66 %	4.66 %	2035
France	5.42 %	5.42 %	2029	5.42 %	4.17 %	2035
Japan	21.97 %	21.97 %	2029	21.79 %	6.05 %	2035
Norway	0.13 %	3.65 %	2029	0.13 %	0.13 %	2035
South Korea	1.81 %	0.00 %	2024	0.00 %	0.00 %	2024
United Kingdom	5.39 %	17.61 %	2029	7.19 %	23.21 %	2035
United States	31.53 %	0.00 %	2028	12.72 %	0.00 %	2030
Emerging economies	11.86 %	14.56 %		11.87 %	14.67 %	
China	8.20 %	0.00 %	2028	8.20 %	5.58 %	2035
Hungary	0.12 %	3.51 %	2029	1.37 %	0.00 %	2033
Indonesia	0.87 %	0.00 %	2024	0.00 %	0.00 %	2028

Source: IMF Climate Data, World Bank, IEA and authors' calculations

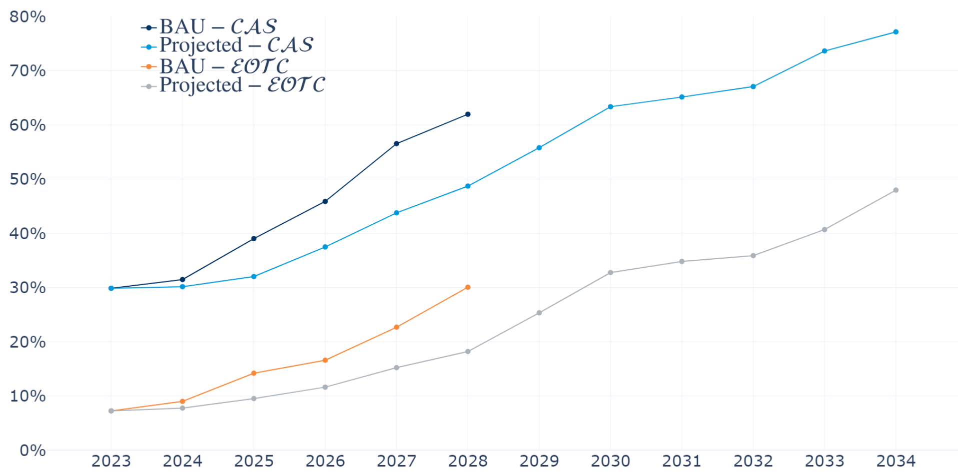
Using projected emissions instead of current emissions has a substantial effect on the weight allocation in the optimised portfolio. We start by looking at the first year a country is removed from the portfolio. In general, some tendencies are similar in the two optimised portfolios. Northern and Western European states are inclined to remain in the portfolio all along the alignment process: this is the case for France, Denmark, the UK or Italy for instance. Symmetrically, the same countries leave the portfolio early (Australia, Canada, Czechia, etc...). It is also worth noting that the US are not present in the final portfolio as they respectively vanish from the allocation in 2028 and 2030 for the BAU and projected emissions cases. However, there are some noticeable changes for some countries. Using projected emissions, China remains in the final portfolio and Indonesia stays until 2028 when it used to leave the portfolio in 2024 in the BAU scenario.

Looking at the precise evolution of the weight allocation is also helpful to get the global picture of what is happening during the alignment process. Once again, the weight evolution by country is quite similar in the BAU and projected emissions cases for European countries and countries that rapidly disappear of the portfolio. Some cases are more interesting though. First, China stays in the portfolio with a relatively consequent weight of 5.58%[2] at the end of the process. This is due to its tremendous GDP growth compared to other countries, therefore it is being advantaged in an "emissions per GDP" scope enhanced in the case of projected emissions. Comparatively, the UK reaches its maximum allowed weight faster in the projected emissions scenario due to a higher decarbonisation than other European countries. On the contrary, Norway that was preferred in the BAU case does not see its weight increase in the projected case. Japan's example is also noteworthy. At first, its weight in the portfolio increases as its carbon intensity is lower than most of its peers and that its weight in the portfolio is significant. However, after a certain time, it starts to decrease due to a lower decarbonisation rate than other states leading to greater emissions per GDP after 7 years.

We can also take note of the natural increase in the portfolio in the "projected case" of the weight proportion of meeting the $\mathcal{EOTC}$ and $\mathcal{CAS}$ criteria.

[1]The full exclusion year table and weight table are available in the appendix (See Table 28 and Table 29).
[2]Which is around two thirds of its original weight in the portfolio.

Figure 34: Evolution of the proportion respecting the $\mathcal{CAS}$ and $\mathcal{EOTC}$ criteria - BAU vs Projected emissions

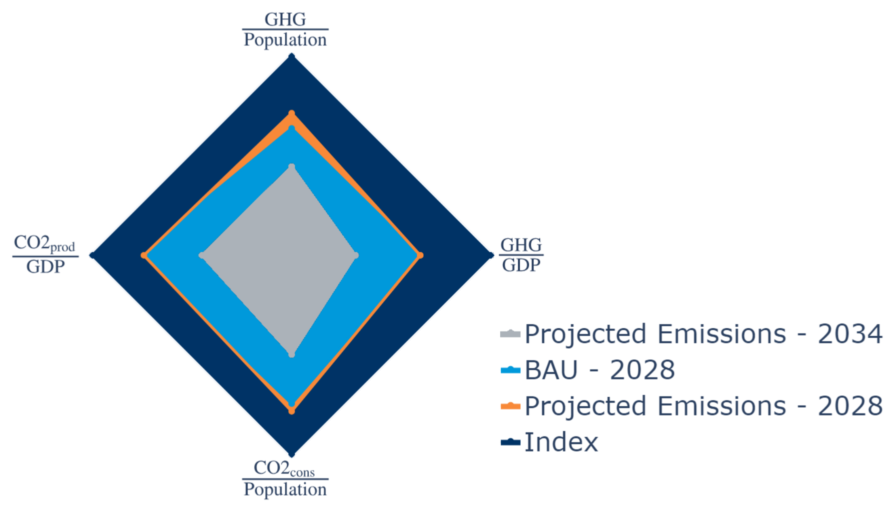


Source: IMF Climate Data, World Bank, IEA, UNFCCC and authors' calculations

In both cases, we are able to reach a more important proportion of the portfolio satisfying the $\mathcal{CAS}$ and $\mathcal{EOTC}$ criteria in the projected emissions case. We also observe that this proportion is increasing alongside the alignment process in all cases, highlighting the good properties of countries with downward trending carbon trends.

As we still compare the main problem in the BAU and projected emissions cases, we look at what happens to the other carbon intensities alongside the alignment process. Figure 35 features the carbon intensity values relatively to the benchmark for the BAU in 2028 and for the projected case in 2028 and 2034. It shows that both problems approximately reach the same carbon intensities in 2028. In fact, when setting only financial and decarbonisation constraints, the carbon intensities mainly depend on the given trajectory and therefore on the given time and year.

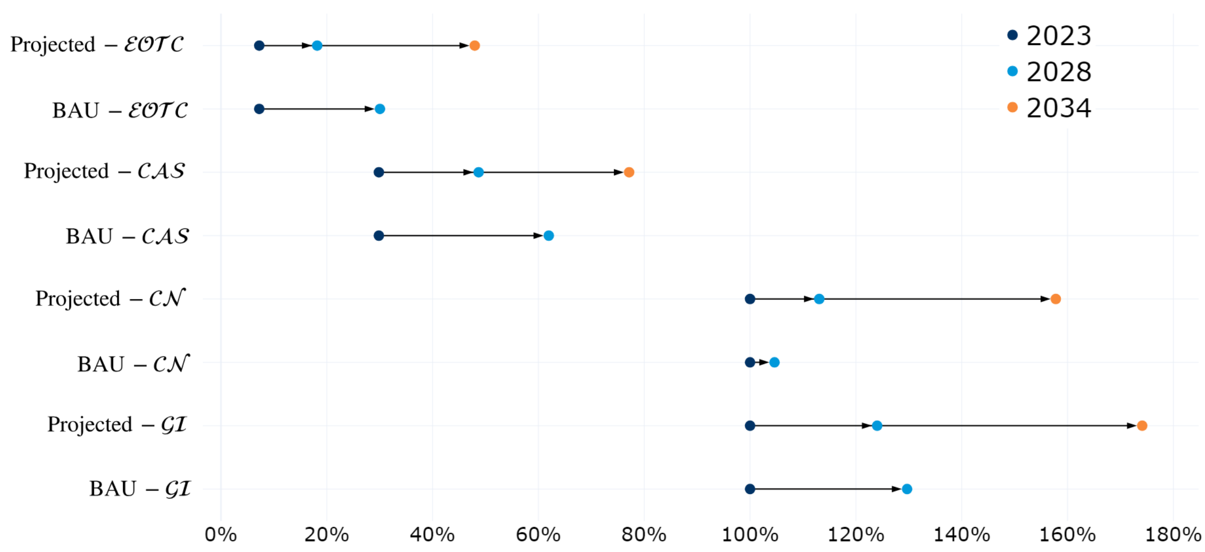
Figure 35: Comparison of carbon intensities relatively to the benchmark - BAU vs Projected emissions



Source: IMF Climate Data, World Bank, IEA and authors' calculations

However, this is slightly different when considering green and other net zero metrics. Figure 36 shows the evolution of some net zero metrics alongside the alignment process depending on the use of fixed or projected emissions. We are still keeping the constraints of the main problem. The greenness $\mathcal{GI}$ and the carbon normalised trend $\mathcal{CN}$ are expressed as percentages of their benchmark's values. $\mathcal{CAS}$ and $\mathcal{EOTC}$ denominations correspond to the proportion of countries respecting these criteria in the optimised portfolios.

Figure 36: Evolution of net zero metrics along the alignment process - BAU vs. Projected emissions



Source: IMF Climate Data, World Bank, IEA, UNFCCC and authors' calculations

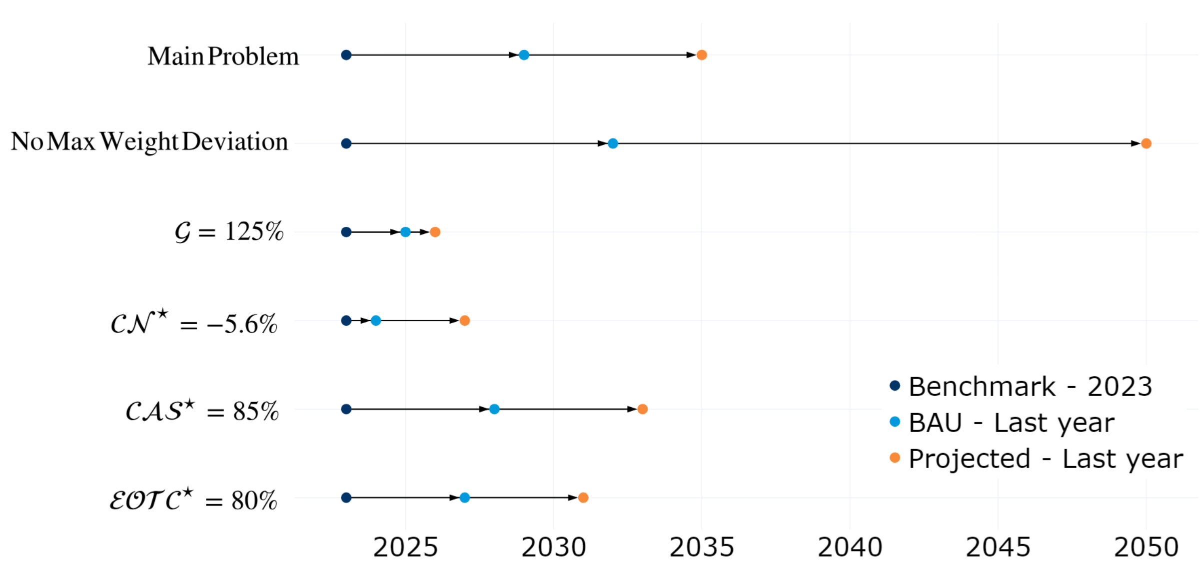
Except for normalised carbon trends, net zero measures are always higher in 2028 for the BAU case than for the case with projected emissions. This is because decarbonisation is the most restrictive constraint and other net zero metrics only need to be better than the benchmark. It is interesting to note that every net zero metrics are naturally moving in the right direction, suggesting that players who have seize the decarbonisation issue are also taking into account all the dimensions of net zero. Only carbon trends in the BAU hypothesis deviates very little from its constraint. We generally observe a larger improvement from 2028 to 2034 than during the first period in the projected emissions case.

It is worth noting that as we use projected emissions, we naturally end up choosing countries with higher rates of decarbonisation only by satisfying constraints on the carbon intensity[1]. This is due to the fact that these countries with steeper negative slopes decarbonise faster than others. Thus, some of them that used to have a mid-range carbon intensity in 2023 end up being amidst the nations with lowest carbon intensities in 2028 and 2034. By taking into account the projected emissions, these countries constitute a greater part of the optimised portfolio in 2028 than what they would have if we only used their rigid carbon intensities in 2023.

6.2.2 Aggregation of all the constraints

In this section, we start by comparing the last obtained year between the BAU and projected emissions cases using several sets of constraints. The problem named "No Max Weight Deviation" in Figure 37 consists in the main problem without the maximum deviation limit. For other, constraints consist of the main problem to which we added the constraint mentioned on the y-axis. For each of the constraints set, we chose the highest possible value for the parameter without the optimiser breaking. In fact, the greatest or lowest usable values for these parameters are almost equal in the BAU and projected emissions cases.

Figure 37: Year of the last solution - BAU vs. Projected Emissions



Source: IMF Climate Data, World Bank, IEA, UNFCCC and authors' calculations

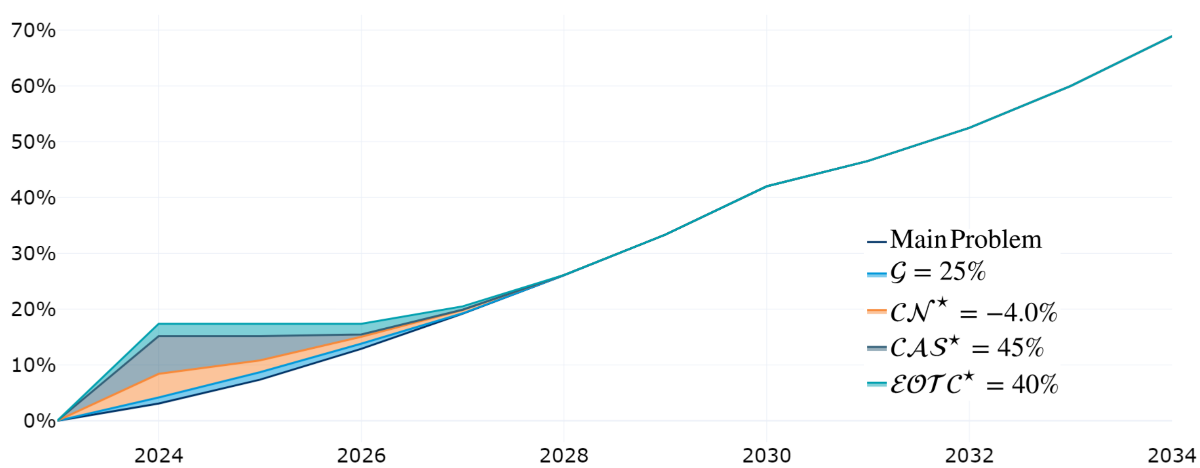
[1]The normalised trends ratio is higher in the case of projected emissions which indicates a lower normalised trend as they are negative in our case.

It is worth observing that by using projected emissions, we are able to fully solve the alignment problem only when the maximum deviation constraint is released. However, as seen in section 6.1.2, it leads to inapplicable solutions in practice. Using projected carbon intensities significantly offers more solution than using current carbon intensities for all problems, except when we impose a high greenness. It would also be possible to use different greenness hypothesis to run our simulation.

We also observe a similar scheme regarding the active share obtained in these problems. Indeed, the obtained active share in the case of the projected emissions is always lower than the BAU's on the comparable period. However, the active share for projected emissions always end up higher than the greatest active share obtained in the BAU scenario.

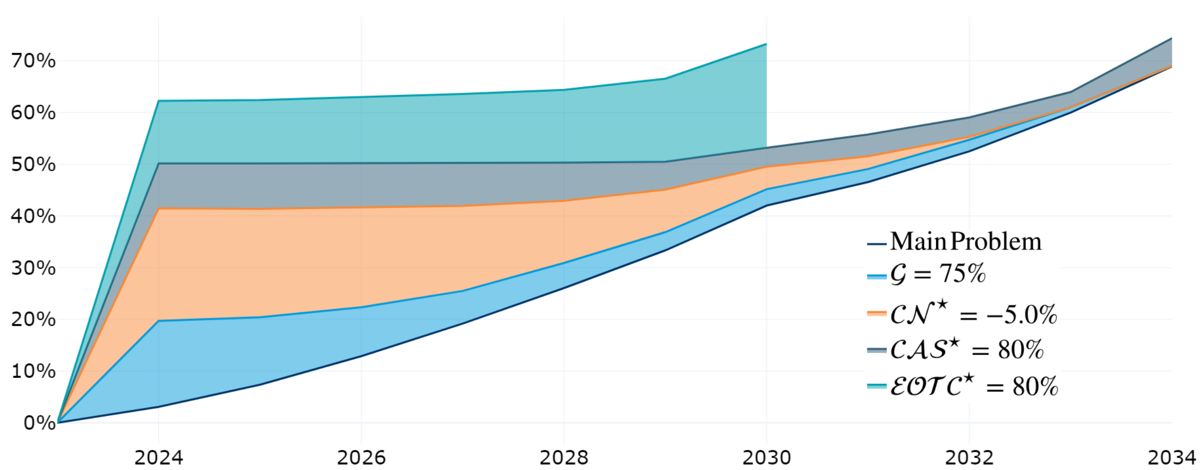
Again, in the case of projected emissions, we can have a look at the marginal contribution of each net zero constraint if we aggregate them successively, from top to bottom in the order of the legend[1]. We use the same sets of constraints as in section 6.1.4.

Figure 38: Marginal contribution of each net zero constraint to additional active share - Projected emissions



Source: IMF Climate Data, World Bank, IEA, UNFCCC and authors' calculations

Figure 39: Marginal contribution of each net zero constraint to additional active share - Projected emissions



Source: IMF Climate Data, World Bank, IEA, UNFCCC and authors' calculations

The first graph shows that by using projected emissions even the problem with all aggregated constraints has a solution until 2034. Moreover, adding all these constraints only leads to a noticeable difference in active share for the first four years. The main leap happens the first year with an additional active share of 11%.

An interesting observation dealing with the second graph is that except for the last problem, the optimiser finds a solution until 2034 which is a difference compared to the BAU. Furthermore, the difference in active share between the main problem and the most constrained problem largely diminishes over time. Using a "projected emissions" framework allows us to impose strong constraints on our problem for longer.

[1] The last problem obtained is described by Table 30 in the appendix.

Conclusion

In this paper, we present a framework to align sovereign bond portfolios with a net zero trajectory. To carry out our analysis, we started by exploring several public databases that offer a significant historical context and the necessary breadth of coverage to build net zero indicators. We then considered various decarbonisation pathways, which are the cornerstone of net zero alignment. After that, we then proposed a model to align a sovereign bond portfolio while maintaining the same financial characteristics as a reference portfolio. Finally, we applied our framework to a global universe. Running a series of simulations allowed us to highlight the difficulties that investors are likely to face while aligning a portfolio. We used two basic assumptions for our case studies: if carbon intensities remain at the same level for each country, and if countries pursue their past decarbonisation efforts.

As net zero alignment is a relatively recent topic, especially for sovereign bonds, we adopted a forward-looking analysis rather than simply carrying out a backtest. Indeed, in our view, a backward-looking analysis does not provide a realistic picture of the potential risks that could arise during the net zero alignment process, as very few financial institutions have started to significantly decarbonise their sovereign bond portfolios. Moreover, the world has just begun the transition towards a low carbon economy, meaning that the greatest financial risks still lie ahead.

The first conclusion that we drew from our analysis is that it is necessary to impose significant constraints on the optimisation programme. Otherwise, the resulting net zero portfolios may appear unrealistic for investors. In general, portfolio alignment is a constrained exercise, and this is even more true for sovereign bonds. For example, large financial institutions tend to hold large amounts of local sovereign debt, which leaves little room for the expansion of the investment universe and involves the integration of country deviation constraints. Financial characteristics such as yields, rating and duration can also deviate significantly if left unconstrained, thus modifying the risk profile of the net zero portfolio compared to the initial one. It is thus important to anticipate those biases before aligning an investment portfolio.

We also highlighted that the choice of the carbon metric is fundamental for net zero alignment. We obtained very different results when we varied the carbon metrics (production, consumption or total emissions) and the normalisation metrics (by population or by GDP). Production-based metrics tend to favour developed countries because their industries are more efficient, and they have relocated carbon-intensive activities overseas. In contrast, consumption-based carbon metrics favour emerging countries which tend to have more carbon-efficient consumption habits. The exclusion year of some countries is also very sensitive to this choice. Moreover, considering carbon emissions or carbon intensities paints very different pictures of the carbon dynamics. It is thus very important to carefully choose the way of counting carbon emissions for sovereigns, or even to run simulations using different metrics. Unfortunately, there is no consensus on carbon accounting for sovereign bonds yet, even though this is fundamental for net zero alignment.

Simulations also highlight the financial risks that can arise from the alignment process. The most obvious one is the tracking risk. Imposing portfolio rebalancing inevitably leads to a performance gap compare to the reference portfolio. Indeed, we observed a significant increase in the active share all along the decarbonisation pathway in all of our simulations. But the tracking risk is not the only financial risk to monitor. We noticed a clear concentration trend across our simulations. Countries with the worst carbon/greenness profiles are excluded from the first year, and the allocation concentrates progressively around the best profiles through time. Liquidity risks may also arise if large financial institutions decide to turn away from some countries' debt based on their large carbon emissions or poor greenness.

Beyond the tracking risk, it is important to note that we are not able to find solutions to our net zero problem until 2050. This means that we cannot achieve decarbonisation from rebalancing all along the net zero pathway, highlighting that it is urgent to decarbonise the economy if we want to limit the temperature rise to 1.5°C. However, if each country undertakes an alignment process, including decarbonisation according to our carbon reduction pathway, better green metrics, more ambitious NDCs and a steeper negative carbon trend, sovereign bond portfolios will naturally be net zero aligned. However, this inability to align our initial portfolio is corroborated by the fact that scenarios in which each country respects its NDCs are generally compatible with a temperature rise of around 2.7°C. In such scenarios, both the IEA and the NGFS have indicated that it will be very difficult to align sovereign portfolios in the future, unless profound and far-reaching changes are made.

We also draw the same conclusion as Barahhou et al. (2022) [11] regarding the fact that net zero alignment is clearly an exclusion process. Independently of the set of constraints chosen, countries with the worst carbon and greenness profiles are systematically excluded from the portfolio, sometimes as soon as year one.

However, considering the projected carbon intensities to run simulations significantly improves the risk metrics of net zero portfolios. In fact, it can be seen as too much stringent to simulate the behaviour of net zero portfolios considering constant carbon intensities over time. Besides, many countries have downward-sloping past carbon emissions, which argues in favour of the projection method. Nonetheless, we observed a clear rebound in global carbon emissions after the COVID-19 crisis, reminding us that different scenarios have to be explored. One drawback of emission projections is the inherent difficulty involved in anticipating and forecasting carbon emissions. With their short history and low frequency, many statistical models cannot be used to project it. One simple solution is then the linear projection method, but other trajectories may be explored. In fact, it is easier to reduce carbon emissions upon departure because some quick wins can be identified. Thereafter, the decarbonisation process becomes more and more challenging.

Simulations are important to anticipate the future behaviour of net zero portfolios and identify potential negative externalities. For example, constraining only decarbonisation may reduce the greenness of the portfolio or underweight players that have made strong and realistic commitments. The net zero process can also overweight low carbon players with an upward trending carbon trend. These side effects create a greenwashing risk for asset owners and managers, and in turn, potential reputational risks. Other ESG issues can also be taken into account, such as respect for human rights, biodiversity, controversial weapons, or corruption.

There is still a debate underway today about whether financial institutions should align their sovereign bond portfolios with a net zero trajectory or simply exclude this asset class from their alignment effort. However, as shown by Collender et al. (2022) [5], transition risks will become increasingly significant for the sovereign bond market, which could ultimately force investors to take these risks into account when managing their portfolios in the future. We have shown in this paper that unless there is a significant improvement in countries' behaviours, the main sovereign bond universe will be highly incompatible with an increase in global temperature below 1.5°C. It is thus important to improve climate data quality and develop alignment methodologies for sovereign bonds.

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Technical Appendix

A Tables of notations

Table 16: Organizations and scenario notations' table

Symbol	**Description**
APC	Announced Pledges Case Scenario
COFOG	Classifications of Functions of Government
CTB	Climate transition benchmark
EIB	European Investment Bank
ESG	Environment, Social and Governance
GHG	Greenhouse Gas
IEA	International Energy Agency
IMF	International Monetary Fund
IPCC	Intergovernmental Panel on Climate Change
ND GAIN	Notre Dame Global Adaptation Initiative
NDC	Nationally Determined Contributions
NGFS	Network for Greening the Financial System
NZ	Net Zero
PAB	Paris-aligned benchmark
STEP	Stated Policies Scenario
SOE	State Owned Enterprises
TEG	Technical expert group
UNFCCC	United Nations Framework Convention on Climate Change
WEO	World Economic Outlook

Table 17: Metric notations' table

Symbol	**Description**
w_j	Country weight in the portfolio
x_i	Bond weight in the portfolio
b_i	Bond weight in the benchmark
$\mathcal{CE}$	Carbon emissions
$\mathcal{CE}_{port}$	Portfolio carbon footprint
$\mathcal{CI}$	Carbon intensity
R	Carbon reduction rate
β_1	Trends
$\mathcal{CN}$	Carbon normalized trends
$\mathcal{GI}$	Greenness
$\mathcal{G}$	Greenness growth rate
$\mathcal{CAS}$	Commitments Aligned with the Scenario
$\mathcal{EOTC}$	Emissions On Track with Commitments
GDP	Gross Domestic Product
AS	Active Share
TE	Tracking error variance
$\mathfrak{D}$	Set of duration buckets
$\mathfrak{R}$	Set of rating buckets
$C_{\mathcal{CI}}$	Contribution to the carbon intensity

B Mathematical results

B.1 Computing the carbon intensity of a portfolio

For a given intensity $\mathcal{CI}$, we recall that:

$$\mathcal{CI}_{(port)} = \sum_{j=1}^{m} w_j \mathcal{CI}_j$$

Therefore, we have by linearity of the coefficient's estimation in the linear regression:

$$\begin{aligned}
\mathcal{CN}_{(port)} &= \frac{\beta_{(port)}}{\mathcal{CI}_{(port)}} \\
&= \frac{\sum_{j=1}^{m} w_j \beta_j}{\mathcal{CI}_{(port)}} \\
&= \frac{\sum_{j=1}^{m} \left(w_j \mathcal{CI}_j\right) \mathcal{CN}_j}{\sum_{j=1}^{m} x_j \mathcal{CI}_j} \\
&= \sum_{j=1}^{m} \left(\frac{w_j \mathcal{CI}_j}{\sum_{k=1}^{m} w_k \mathcal{CI}_k} \right) \mathcal{CN}_j \\
&= \sum_{j=1}^{m} \left(\frac{w_j \mathcal{CI}_j}{\mathcal{CI}_{(port)}} \right) \mathcal{CN}_j
\end{aligned}$$

As done in Barahhou et al. (2022) [11], we can then write:

$$\mathcal{CN}_{(port)} = \sum_{j=1}^{m} \bar{w}_j \, \mathcal{CN}_j$$

where

$$\bar{w}_j = \frac{w_j \, \mathcal{CI}_j}{\sum_{k=1}^{m} w_k \mathcal{CI}_k} = \frac{w_j \, \mathcal{CI}_j}{\mathcal{CI}_{(port)}}$$

B.2 Turning a problem with absolute values into an LP problem

We start from the initial active-share problem:

$$\begin{aligned}
x^\star = \quad & \underset{x}{\textbf{argmin}} \quad \frac{1}{2} \sum_{i=1}^{n} |x_i - b_i| \\
& \textbf{subject to} \quad \begin{cases} Gx & \leq h \\ Cx & = d \end{cases}
\end{aligned}$$

By noting that the two following simple problems are equivalent:

$$\min_{x} |x - b| \qquad \text{and} \qquad \left| \begin{array}{l} \min_{(x,\tau)} \tau \\ \textbf{s.t.} \begin{cases} x - \tau \leq b \\ -x - \tau \leq -b \end{cases} \end{array} \right.$$

we can rewrite our active-share portfolio problem as an LP problem:

$$\begin{aligned}
& \underset{(x,\tau)}{\textbf{minimize}} \quad \begin{pmatrix} \mathbf{0}_n^T & \mathbf{1}_n^T \end{pmatrix} \begin{pmatrix} x \\ \tau \end{pmatrix} \\
& \textbf{subject to} \quad \begin{cases} \begin{pmatrix} G & 0 \\ I_n & -I_n \\ -I_n & -I_n \end{pmatrix} \begin{pmatrix} x \\ \tau \end{pmatrix} \leq \begin{pmatrix} h \\ b \\ -b \end{pmatrix} \\ \begin{pmatrix} C & 0 \end{pmatrix} \begin{pmatrix} x \\ \tau \end{pmatrix} = d \end{cases}
\end{aligned}$$

B.3 Turning a TE problem into a QP problem

We express the TE of a benchmark b with a covariance matrix of returns Σ:

$$TE(x) = (x - b)^T \Sigma (x - b)$$

We then have:

$$\begin{aligned}
TE(x) &= (x - b)^T \Sigma (x - b) \\
&= x^T \Sigma x - x^T \Sigma b - b^T \Sigma x + b^T \Sigma b \\
&= x^T \Sigma x - 2x^T \Sigma b + b^T \Sigma b
\end{aligned}$$

The last line is obtained because $b^T \Sigma x = \left(b^T \Sigma x\right)^T = x^T \Sigma b$ as Σ is symmetric and $b^T \Sigma x \in \mathbb{R}$. The key point to observe now is that adding a constant (here $b^T \Sigma b$) to $TE(x)$ does not change the argument of the minimum $x^\star$ so we can rewrite our TE minimisation problem as:

$$x^\star = \begin{array}{ll} \underset{x}{\textbf{argmin}} & \frac{1}{2}(x-b)^T \Sigma (x-b) \\ \textbf{subject to} & \left\{ \begin{array}{ll} Gx & \leq h \\ Cx & = d \end{array} \right. \end{array} = \begin{array}{ll} \underset{x}{\textbf{argmin}} & \frac{1}{2} x^T \Sigma x - x^T \Sigma b \\ \textbf{subject to} & \left\{ \begin{array}{ll} Gx & \leq h \\ Cx & = d \end{array} \right. \end{array}$$

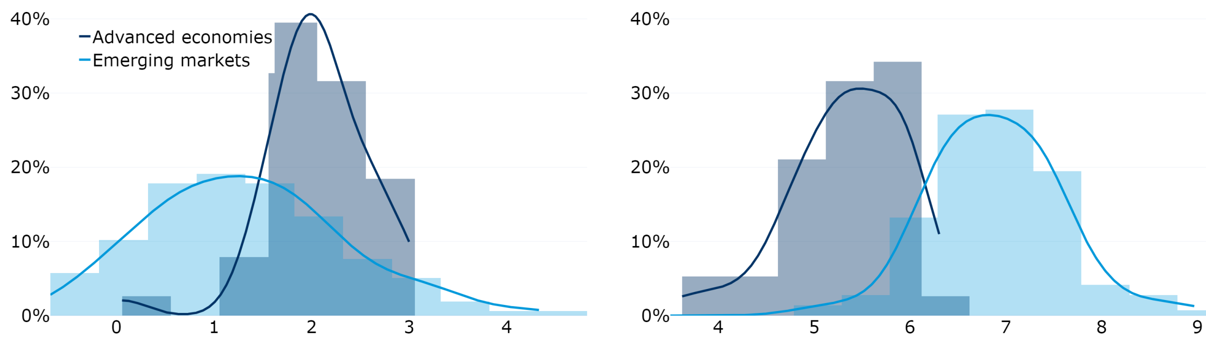
The last problem is indeed a QP problem with $Q = \Sigma$ and $p = -\Sigma b$.

Appendix: Additional Results

A Carbon metrics

A.1 Carbon intensities

Figure 40: Distributions of intensities by development level



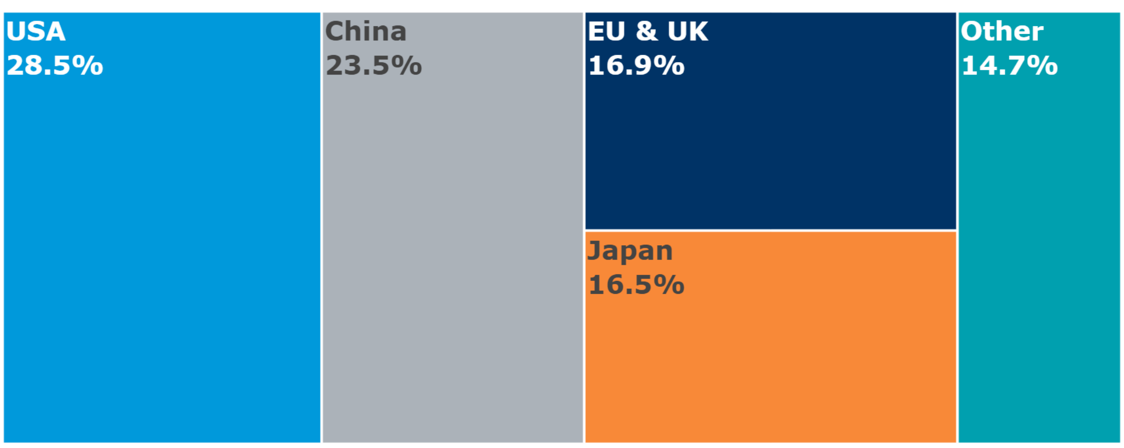
(a) GHG per capita - log(tCO_2eq per capita)

(b) GHG per GDP
log(tCO_2eq per million dollar of GDP)

Source: IMF Climate Data, World Bank and authors' calculations

B Universe

Figure 41: Contribution to the GHG per GDP carbon intensity of the Bloomberg Global Aggregate Treasuries by region

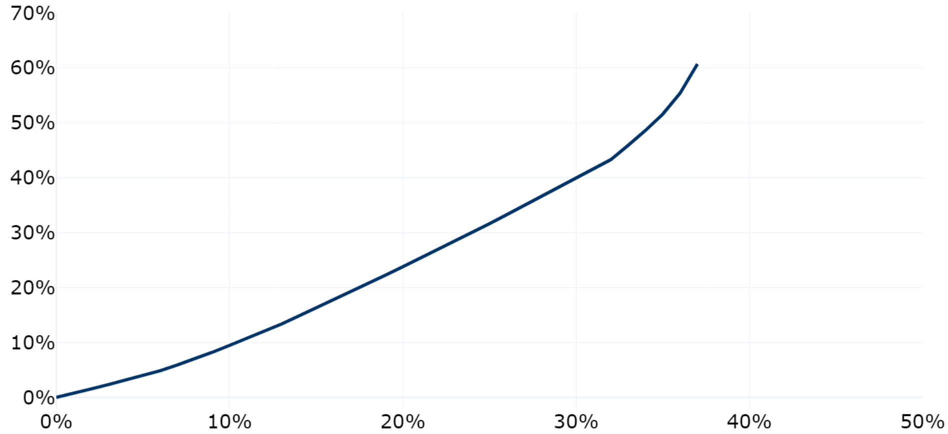


Source: World Bank, IEA and authors' calculations

C Using spot carbon emissions

C.1 Main net zero alignment process

Figure 42: Impact of the carbon reduction rate ($\mathcal{R}$) on the active share of the main net zero problem



Source: IMF Climate Data, World Bank, Bloomberg and authors' calculations

Table 18: Weight table for the main net zero alignment problem

	2023	2024	2025	2026	2027	2028
Advanced economies	88.14%	88.26%	87.98%	87.94%	88.46%	85.44%
Australia	1.55%	0.41%	0.00%	0.00%	0.00%	0.00%
Austria	0.78%	0.78%	0.78%	0.78%	0.78%	0.78%
Belgium	1.21%	1.21%	1.21%	1.21%	1.21%	0.00%
Canada	1.74%	0.00%	0.00%	0.00%	0.00%	0.00%
Cyprus	0.04%	0.04%	0.04%	0.04%	0.04%	0.04%
Czechia	0.27%	0.00%	0.00%	0.00%	0.00%	0.00%
Denmark	0.22%	1.23%	2.23%	4.66%	4.66%	4.66%
Estonia	0.01%	0.01%	0.00%	0.00%	0.01%	0.00%
Finland	0.33%	0.33%	0.33%	0.33%	0.33%	0.33%
France	5.42%	5.42%	5.42%	5.42%	5.42%	5.42%
Germany	4.21%	4.21%	4.21%	4.21%	4.21%	4.21%
Hong Kong	0.03%	0.03%	0.03%	1.59%	1.59%	1.59%
Ireland	0.41%	0.41%	0.41%	2.28%	6.43%	6.43%
Israel	0.21%	0.21%	0.21%	0.21%	0.69%	2.75%
Italy	4.91%	5.02%	4.91%	4.91%	4.91%	3.66%
Japan	21.97%	21.97%	21.97%	21.97%	21.97%	21.97%
Latvia	0.04%	0.04%	0.04%	0.04%	0.04%	0.00%
Lithuania	0.03%	0.03%	0.00%	0.00%	0.00%	0.00%
Luxembourg	0.05%	0.05%	0.05%	2.21%	2.21%	2.21%
Malta	0.00%	0.00%	0.04%	0.00%	0.04%	0.04%
Netherlands	0.99%	0.99%	0.99%	0.99%	0.99%	0.99%
New Zealand	0.22%	0.00%	0.00%	0.00%	0.00%	0.00%
Norway	0.13%	0.13%	2.49%	3.65%	3.65%	3.65%
Portugal	0.45%	0.45%	0.45%	0.45%	0.45%	0.00%
Singapore	0.31%	0.31%	0.31%	0.31%	0.31%	0.16%
Slovakia	0.16%	0.16%	0.00%	0.00%	0.00%	0.00%
Slovenia	0.10%	0.10%	0.10%	0.10%	0.10%	0.00%
South Korea	1.81%	0.00%	0.00%	0.00%	0.00%	0.00%
Spain	3.24%	3.24%	3.24%	3.24%	3.24%	0.00%
Sweden	0.14%	0.14%	3.80%	3.80%	3.80%	3.80%
Switzerland	0.25%	4.41%	5.01%	5.01%	5.01%	5.01%
United Kingdom	5.39%	5.39%	5.39%	5.39%	11.58%	17.76%
United States	31.53%	31.53%	24.32%	15.16%	4.82%	0.00%
Emerging economies	11.86%	11.74%	12.02%	12.06%	11.54%	14.56%
Chile	0.11%	0.11%	1.11%	2.72%	3.28%	3.28%
China	8.20%	8.20%	7.37%	5.79%	4.71%	0.00%
Colombia	0.16%	0.16%	0.16%	0.16%	0.16%	0.16%
Hungary	0.12%	0.88%	1.57%	1.57%	1.57%	3.51%
Indonesia	0.87%	0.00%	0.00%	0.00%	0.00%	0.00%
Malaysia	0.69%	0.69%	0.69%	0.69%	0.69%	0.00%
Mexico	0.58%	0.58%	0.58%	0.58%	0.58%	0.58%
Peru	0.10%	0.10%	0.10%	0.10%	0.10%	3.10%
Poland	0.31%	0.31%	0.31%	0.31%	0.31%	3.79%
Romania	0.14%	0.14%	0.14%	0.14%	0.14%	0.14%
Thailand	0.58%	0.58%	0.00%	0.00%	0.00%	0.00%

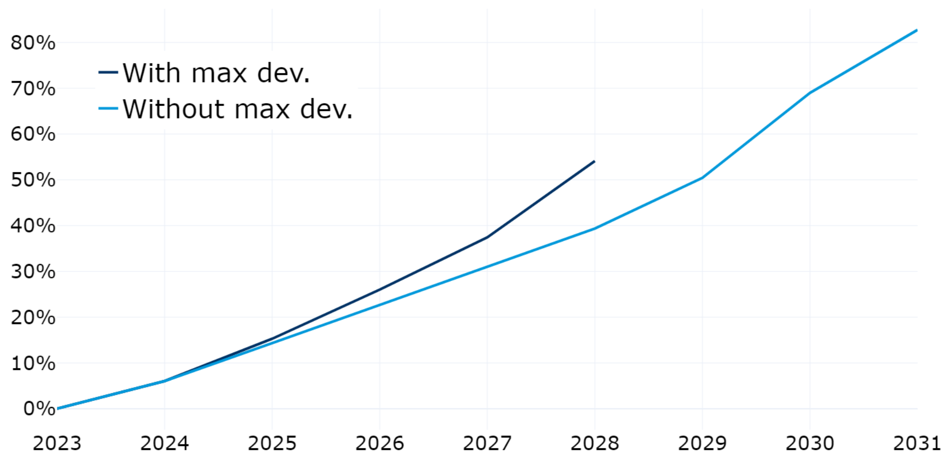
Source: IMF Climate Data, World Bank, IEA and authors' calculations

C.2 Problem's sensitivity to the current constraints

Table 19: Main problem without maximum deviation constraints - Table of constraints

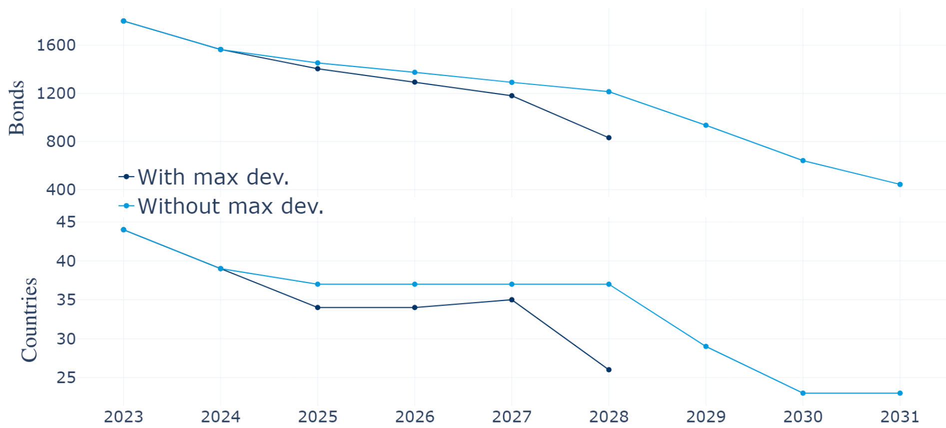
Type	Name	Value
Weights	Long-only	✓
	No leverage	✓
	Min weight deviation by country	✘
	Max weight deviation by country	✘
	Proportion of advanced countries	✘
Financial	Duration	Same buckets
	Ratings	Same buckets
	Yields	Within a 10% relative interval
Decarbonisation	$\frac{\text{GHG}}{\text{GDP}}$ intensity	IEA Net Zero Scenario
Transition	Greenness	$\mathcal{G} = 0$
	Trend	✘
	$\mathcal{CAS}$	✘
	$\mathcal{EOTC}$	✘

Figure 43: Active share comparison - Main problem with and without maximum deviation constraints



Source: IMF Climate Data, World Bank, Bloomberg and authors' calculations

Figure 44: Bonds and countries - Main net zero alignment problem with and without maximum deviation constraints



Source: IMF Climate Data, World Bank, IEA and authors' calculations

Table 20: Weight variation due to the maximum deviation constraints in the last obtained portfolio

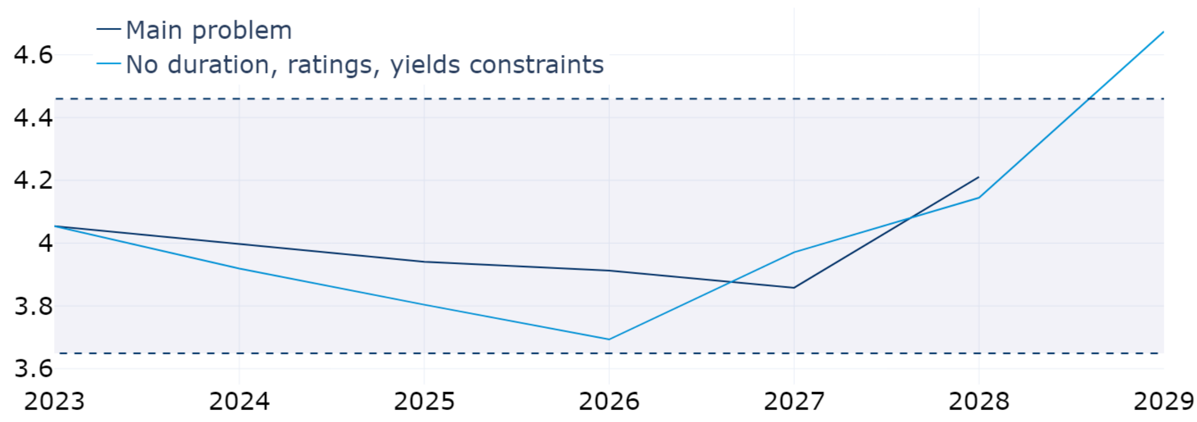
	With max. dev.	Without max. dev.	Difference
Advanced economies	85.44 %	88.64 %	3.20 %
Australia	0.00 %	0.00 %	0.00 %
Austria	0.78 %	0.00 %	-0.78 %
Belgium	0.00 %	0.00 %	0.00 %
Canada	0.00 %	0.00 %	0.00 %
Switzerland	5.01 %	40.28 %	35.26 %
Cyprus	0.04 %	0.04 %	-0.00 %
Czechia	0.00 %	0.00 %	0.00 %
Germany	4.21 %	0.00 %	-4.21 %
Denmark	4.66 %	10.58 %	5.92 %
Spain	0.00 %	3.24 %	3.24 %
Estonia	0.00 %	0.00 %	0.00 %
Finland	0.33 %	0.00 %	-0.33 %
France	5.42 %	0.00 %	-5.42 %
United Kingdom	17.76 %	5.39 %	-12.38 %
Hong Kong	1.59 %	0.03 %	-1.56 %
Ireland	6.43 %	0.41 %	-6.01 %
Israel	2.75 %	0.21 %	-2.54 %
Italy	3.66 %	4.91 %	1.25 %
Japan	21.97 %	0.73 %	-21.23 %
South Korea	0.00 %	0.00 %	0.00 %
Lithuania	0.00 %	0.03 %	0.03 %
Luxembourg	2.21 %	0.03 %	-2.18 %
Latvia	0.00 %	0.00 %	0.00 %
Malta	0.04 %	22.25 %	22.22 %
Netherlands	0.99 %	0.00 %	-0.99 %
Norway	3.65 %	0.13 %	-3.51 %
New Zealand	0.00 %	0.00 %	0.00 %
Portugal	0.00 %	0.24 %	0.24 %
Singapore	0.16 %	0.00 %	-0.16 %
Slovakia	0.00 %	0.00 %	0.00 %
Slovenia	0.00 %	0.00 %	0.00 %
Sweden	3.80 %	0.14 %	-3.66 %
United States	0.00 %	0.00 %	0.00 %
Emerging economies	14.56 %	11.36 %	3.20 %
Chile	3.28 %	8.29 %	5.01 %
China	0.00 %	0.00 %	0.00 %
Colombia	0.16 %	0.11 %	-0.05 %
Hungary	3.51 %	2.06 %	-1.44 %
Indonesia	0.00 %	0.00 %	0.00 %
Mexico	0.58 %	0.35 %	-0.23 %
Malaysia	0.00 %	0.00 %	0.00 %
Peru	3.10 %	0.10 %	-3.00 %
Poland	3.79 %	0.31 %	-3.48 %
Romania	0.14 %	0.14 %	-0.00 %
Thailand	0.00 %	0.00 %	0.00 %

Source: IMF Climate Data, World Bank, IEA and authors' calculations

Table 21: Main net zero problem without duration, rating and yield constraints - Table of constraints

Type	Name	Value
Weights	Long-only	✓
	No leverage	✓
	Min Weight deviation by country	✘
	Max weight deviation by country	✓
	Proportion of advanced countries	Within a 5% relative interval
Financial	Duration	✘
	Ratings	✘
	Yields	✘
Decarbonisation	$\frac{\text{GHG}}{\text{GDP}}$ intensity	IEA Net Zero Scenario
Transition	Greenness	$\mathcal{G} = 0$
	Trend	✘
	$\mathcal{CAS}$	✘
	$\mathcal{EOTC}$	✘

Figure 45: Yield to maturity comparison - Main net zero problem with and without duration, rating and yield constraints

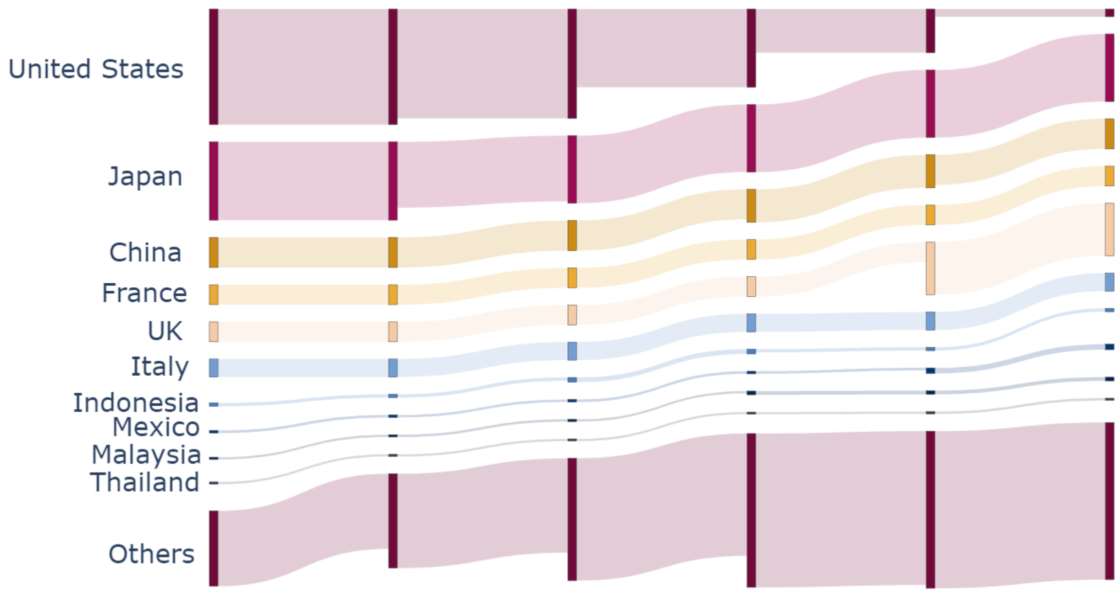


Source: IMF Climate Data, World Bank, Bloomberg and authors' calculations

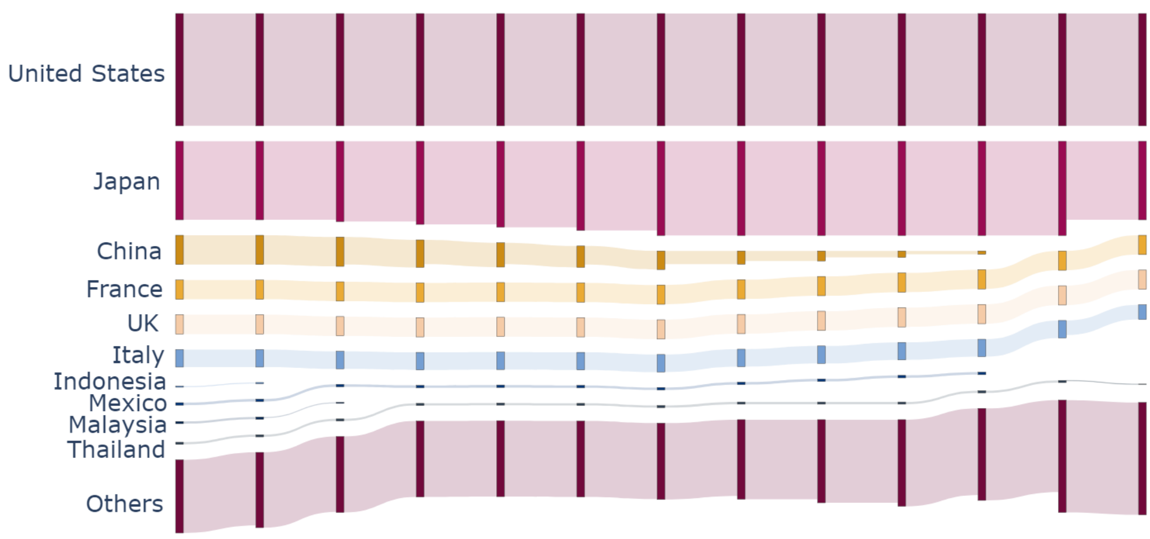
Table 22: Main net zero alignment problem constraining only advanced/emerging economies - Table of constraints

Type	Name	Value
Weights	Long-only	✓
	No leverage	✓
	Min weight deviation by country	✘
	Max weight deviation by country	✓
	Proportion of advanced countries	Within a 5% relative interval
Financial	Duration	Same buckets
	Ratings	Same buckets
	Yields	Within a 10% relative interval
Decarbonisation	$\frac{\text{GHG}}{\text{GDP}}$ intensity	Advanced or Emerging IEA Net Zero Scenario
Transition	Greenness	$\mathcal{G} = 0$
	Trend	✘
	$\mathcal{CAS}$	✘
	$\mathcal{EOTC}$	✘

Figure 46: Weight evolution for top 5 advanced and emerging countries in the Bloomberg Global Aggregate Treasuries- Main net zero problem constraining only advanced or emerging



(a) Only advanced



(b) Only emerging

Source: IMF Climate Data, World Bank, IEA and authors' calculations

Table 23: Main net zero alignment problem with varying intensity - Table of constraints

Type	**Name**	**Value**
Weights	Long-only No leverage Min weight deviation by country Max weight deviation by country Proportion of advanced countries	✓ ✓ ✘ ✓ Within a 5% relative interval
Financial	Duration Ratings Yields	Same buckets Same buckets Within a 10% relative interval
Decarbonisation	*Changing intensity*[1]	IEA Net Zero Scenario
Transition	Greenness Trend $\mathcal{CAS}$ $\mathcal{EOTC}$	$\mathcal{G} = 0$ ✘ ✘ ✘

[1] We successively use one of the four usual intensities.

Table 24: Exclusion year by country by used carbon intensity in the main net zero problem

	$\frac{\mathbf{CO2_{cons}}}{\mathbf{Population}}$	$\frac{\mathbf{CO2_{prod}}}{\mathbf{GDP}}$	$\frac{\mathbf{GHG}}{\mathbf{Population}}$	$\frac{\mathbf{GHG}}{\mathbf{GDP}}$
Advanced economies				
Australia	2024	2027	2025	2024
Austria	2031	2027	2029	2031
Belgium	2031	2027	2028	2031
Canada	2024	2024	2024	2030
Cyprus	2031	2027	2029	2032
Czechia	2030	2024	2024	2030
Denmark	2030	2027	2029	2032
Estonia	2029	2024	2025	2032
Finland	2030	2027	2029	2031
France	2031	2027	2029	2032
Germany	2031	2027	2029	2031
Hong Kong	2030	2024	2029	2032
Ireland	2030	2027	2029	2030
Israel	2031	2027	2029	2032
Italy	2030	2027	2029	2031
Japan	2031	2027	2029	2032
Latvia	2031	2025	2028	2032
Lithuania	2031	2025	2025	2032
Luxembourg	2024	2027	2029	2030
Malta	2031	2025	2029	2032
Netherlands	2030	2027	2029	2031
New Zealand	2031	2027	2024	2030
Norway	2030	2027	2029	2031
Portugal	2031	2025	2028	2031
Singapore	2024	2027	2029	2030
Slovakia	2031	2024	2025	2032
Slovenia	2031	2025	2028	2032
South Korea	2030	2024	2024	2030
Spain	2030	2027	2028	2031
Sweden	2031	2027	2029	2032
Switzerland	2031	2027	2029	2032
United Kingdom	2031	2027	2029	2032
United States	2029	2026	2028	2030
Emerging economies				
Chile	2031	2027	2029	2032
China	2031	2027	2028	2031
Colombia	2031	2027	2029	2032
Hungary	2030	2027	2029	2031
Indonesia	2031	2024	2024	2032
Malaysia	2026	2027	2028	2032
Mexico	2031	2027	2029	2032
Peru	2031	2027	2029	2032
Poland	2025	2027	2029	2031
Romania	2031	2027	2029	2031
Thailand	2031	2026	2025	2032

Source: IMF Climate Data, World Bank, IEA and authors' calculations

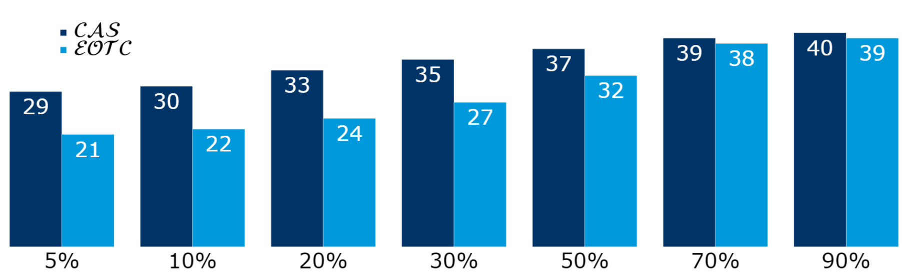
Table 25: Weight Table - Last obtained portfolio for the main net zero problem by used carbon intensity

	$\frac{CO2_{cons}}{Population}$	$\frac{CO2_{prod}}{GDP}$	$\frac{GHG}{Population}$	$\frac{GHG}{GDP}$
Advanced economies	85.23%	88.17%	85.48%	84.88%
Australia	0.00%	1.17%	0.00%	0.00%
Austria	0.78%	0.78%	0.78%	0.00%
Belgium	1.21%	1.21%	0.00%	0.00%
Canada	0.00%	0.00%	0.00%	0.00%
Cyprus	0.04%	0.04%	0.04%	0.04%
Czechia	0.00%	0.00%	0.00%	0.00%
Denmark	0.00%	0.22%	4.66%	0.22%
Estonia	0.00%	0.00%	0.00%	0.01%
Finland	0.00%	0.33%	0.33%	0.00%
France	23.28%	8.92%	5.42%	23.28%
Germany	3.50%	4.21%	4.21%	0.00%
Hong Kong	0.00%	0.00%	1.59%	1.59%
Ireland	0.00%	6.43%	6.43%	0.00%
Israel	0.21%	0.29%	2.31%	0.21%
Italy	0.00%	4.91%	3.77%	0.00%
Japan	19.72%	21.97%	21.97%	16.33%
Latvia	1.88%	0.04%	0.00%	1.88%
Lithuania	1.86%	0.00%	0.00%	1.86%
Luxembourg	0.00%	0.05%	2.21%	0.00%
Malta	0.00%	0.00%	0.41%	0.41%
Netherlands	0.00%	0.99%	0.99%	0.00%
New Zealand	0.22%	0.22%	0.00%	0.00%
Norway	0.00%	0.13%	3.65%	0.00%
Portugal	0.45%	0.45%	0.00%	0.00%
Singapore	0.00%	0.31%	0.31%	0.00%
Slovakia	3.99%	0.16%	0.00%	3.93%
Slovenia	0.10%	0.10%	0.00%	3.23%
South Korea	0.00%	0.00%	0.00%	0.00%
Spain	0.00%	3.24%	0.00%	0.00%
Sweden	3.80%	3.80%	3.80%	3.80%
Switzerland	5.01%	5.01%	5.01%	5.01%
United Kingdom	19.19%	23.21%	17.61%	23.09%
United States	0.00%	0.00%	0.00%	0.00%
Emerging economies	14.77%	11.83%	14.52%	15.12%
Chile	0.11%	3.28%	3.28%	3.28%
China	3.95%	5.00%	0.00%	0.00%
Colombia	4.03%	1.61%	0.16%	4.03%
Hungary	0.00%	0.12%	3.51%	0.00%
Indonesia	2.27%	0.00%	0.00%	3.44%
Malaysia	0.00%	0.69%	0.00%	0.69%
Mexico	0.58%	0.58%	0.58%	0.58%
Peru	3.10%	0.10%	3.00%	3.10%
Poland	0.00%	0.31%	3.86%	0.00%
Romania	0.14%	0.14%	0.14%	0.00%
Thailand	0.58%	0.00%	0.00%	0.01%

Source: IMF Climate Data, World Bank, IEA and authors' calculations

C.3 Addition of other net zero metrics

Figure 47: Number of countries respecting the $\mathcal{CAS}$ and $\mathcal{EOTC}$ criteria according to the given percentage of tolerance



Source: IMF Climate Data, World Bank, IEA and authors' calculations

C.4 Aggregation of all the constraints

Table 26: Full net zero alignment problem - Table of constraints

Type	Name	Value
Weights	Long-only	✓
	No leverage	✓
	Min weight deviation by country	✘
	Max weight deviation by country	✓
	Proportion of advanced countries	Within a 5% relative interval
Financial	Duration	Same buckets
	Ratings	Same buckets
	Yields	Within a 10% relative interval
Decarbonisation	$\frac{\text{GHG}}{\text{GDP}}$ intensity	IEA Net Zero Scenario
Transition	Greenness	$\mathcal{G} = 50\%$
	Trend	$\leq \mathcal{CN}^{\star} = -4.5\%$
	$\mathcal{CAS}$	$\geq \mathcal{CAS}^{\star} = 60\%$
	$\mathcal{EOTC}$	$\geq \mathcal{EOTC}^{\star} = 60\%$

D Using projected carbon emissions

D.1 Main net zero alignment process

Table 27: Main net zero alignment problem - Projected emissions - Table of constraints

Type	Name	Value
Weights	Long-only	✓
	No leverage	✓
	Min weight deviation by country	✘
	Max weight deviation by country	✓
	Proportion of advanced countries	Within a 5% relative interval
Financial	Duration	Same buckets
	Ratings	Same buckets
	Yields	Within a 10% relative interval
Decarbonisation	Projected $\frac{\text{GHG}}{\text{GDP}}$ intensity	IEA Net Zero Scenario
Transition	Greenness	$\mathcal{G} = 0$
	Trend	✘
	$\mathcal{CAS}$	✘
	$\mathcal{EOTC}$	✘

Table 28: First year out of the portfolio by country - BAU vs. Projected

Advanced eco.									Emerging eco.		
	BAU	PE[1]		BAU	PE		BAU	PE		BAU	PE
Australia	2025	2025	Hong Kong	2029	2035	New Zealand	2024	2025	Chile	2029	2033
Austria	2029	2032	Ireland	2029	2035	Portugal	2028	2030	China	2028	2035
Belgium	2028	2032	Israel	2029	2035	Singapore	2029	2030	Colombia	2029	2032
Canada	2024	2025	Italy	2029	2035	Slovakia	2025	2025	Hungary	2029	2033
Cyprus	2029	2035	Japan	2029	2035	Slovenia	2028	2035	Indonesia	2024	2028
Czechia	2024	2024	Latvia	2028	2026	South Korea	2024	2024	Mexico	2029	2035
Denmark	2029	2035	Lithuania	2025	2026	Spain	2028	2035	Malaysia	2028	2030
Estonia	2025	2035	Luxembourg	2029	2035	Switzerland	2035	2029	Peru	2029	2032
Finland	2029	2035	Malta	2029	2035	Sweden	2029	2035	Poland	2029	2035
France	2029	2035	Netherlands	2029	2032	United Kingdom	2029	2035	Romania	2029	2035
Germany	2029	2034	Norway	2029	2035	United States	2028	2030	Thailand	2025	2029

Source: IMF Climate Data, World Bank, IEA and authors' calculations

[1]Projected emissions.

Table 29: Weight table by country in % - BAU vs Projected

	BAU - 2023	**BAU - 2028**	**Projected - 2028**	**Projected - 2034**
Advanced economies	88.14 %	85.44 %	88.13 %	85.33 %
Australia	1.55 %	0.00 %	0.00 %	0.00 %
Austria	0.78 %	0.78 %	0.78 %	0.00 %
Belgium	1.21 %	0.00 %	1.21 %	0.00 %
Canada	1.74 %	0.00 %	0.00 %	0.00 %
Cyprus	0.04 %	0.04 %	0.04 %	0.04 %
Czechia	0.27 %	0.00 %	0.00 %	0.00 %
Denmark	0.22 %	4.66 %	4.66 %	4.66 %
Estonia	0.01 %	0.00 %	0.01 %	0.86 %
Finland	0.33 %	0.33 %	0.33 %	5.78 %
France	5.42 %	5.42 %	5.42 %	4.17 %
Germany	4.21 %	4.21 %	4.21 %	0.00 %
Hong Kong	0.03 %	1.59 %	1.59 %	1.59 %
Ireland	0.41 %	6.43 %	6.43 %	6.43 %
Israel	0.21 %	2.31 %	0.21 %	4.60 %
Italy	4.91 %	3.77 %	4.91 %	4.08 %
Japan	21.97 %	21.97 %	21.79 %	6.05 %
Latvia	0.04 %	0.00 %	0.00 %	0.00 %
Lithuania	0.03 %	0.00 %	0.00 %	1.86 %
Luxembourg	0.05 %	2.21 %	2.21 %	2.21 %
Malta	0.00 %	0.41 %	0.41 %	0.41 %
Netherlands	0.99 %	0.99 %	0.99 %	0.00 %
New Zealand	0.22 %	0.00 %	0.00 %	0.00 %
Norway	0.13 %	3.65 %	0.13 %	0.13 %
Portugal	0.45 %	0.00 %	0.45 %	0.00 %
Singapore	0.31 %	0.31 %	0.31 %	0.00 %
Slovakia	0.16 %	0.00 %	0.00 %	3.99 %
Slovenia	0.10 %	0.00 %	0.10 %	3.23 %
South Korea	1.81 %	0.00 %	0.00 %	0.00 %
Spain	3.24 %	0.00 %	3.24 %	3.24 %
Sweden	0.14 %	3.80 %	3.80 %	3.80 %
Switzerland	0.25 %	5.01 %	5.01 %	5.01 %
United Kingdom	5.39 %	17.61 %	7.19 %	23.21 %
United States	31.53 %	0.00 %	12.72 %	0.00 %
Emerging economies	11.86 %	14.56 %	11.87 %	14.67 %
Chile	0.11 %	3.28 %	0.11 %	0.00 %
China	8.20 %	0.00 %	8.20 %	5.58 %
Colombia	0.16 %	0.16 %	0.16 %	0.00 %
Hungary	0.12 %	3.51 %	1.37 %	0.00 %
Indonesia	0.87 %	0.00 %	0.00 %	0.00 %
Malaysia	0.69 %	0.00 %	0.69 %	0.00 %
Mexico	0.58 %	0.58 %	0.58 %	0.03 %
Peru	0.10 %	3.00 %	0.10 %	0.00 %
Poland	0.31 %	3.86 %	0.31 %	5.25 %
Romania	0.14 %	0.14 %	0.14 %	3.81 %
Thailand	0.58 %	0.00 %	0.21 %	0.00 %

Source: IMF Climate Data, World Bank, IEA and authors' calculations

D.2 Aggregation of all the constraints

Table 30: Full net zero alignment problem - Projected emissions - Table of constraints

Type	**Name**	**Value**
Weights	Long-only	✓
	No leverage	✓
	Min weight deviation by country	✘
	Max weight deviation by country	✓
	Proportion of advanced countries	Within a 5% relative interval
Financial	Duration	Same buckets
	Ratings	Same buckets
	Yields	Within a 10% relative interval
Decarbonisation	Projected $\frac{\text{GHG}}{\text{GDP}}$ intensity	IEA Net Zero Scenario
Transition	Greenness	$\mathcal{G} = 50\%$
	Trend	$\leq \mathcal{CN}^{\star} = -4.5\%$
	$\mathcal{CAS}$	$\geq \mathcal{CAS}^{\star} = 60\%$
	$\mathcal{EOTC}$	$\geq \mathcal{EOTC}^{\star} = 60\%$