Net Zero Investment Portfolios – Part 2. The Core-Satellite Approach*

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Abstract

This article is the second part of a research project on net-zero investment. While the previous publication was dedicated to the integrated approach, this one focuses on the core-satellite approach. As explained in the first part, net-zero policies need to address two dimensions: decarbonizing the portfolio and financing the transition. The integrated approach combines these two dimensions in an allocation process that considers both carbon intensity for the decarbonisation dimension and green intensity for the financing dimension. However, we have found that carbon intensity and green intensity are currently positively correlated. Therefore, we propose a second approach to better identify the contribution of the two net-zero dimensions. In the core-satellite strategy, the decarbonization dimension is managed within the core portfolio, while the objective of the satellite strategy is to finance the transition to a low-carbon economy.

The choice of the decarbonization policy is an important step in the design of the core portfolio. At least, three issues need to be considered: the magnitude of the decarbonization pathway, the sequence of decarbonization, and the self-decarbonization property of the core portfolio. Moreover, a decarbonization pathway is not neutral if we refer to a strategic asset allocation process. In fact, it is equivalent to changing the implied risk premia derived from the Black-Litterman model. Building the satellite portfolio is certainly the most challenging part of the allocation process. It requires a deeper understanding of how to achieve net-zero emissions by 2050, specifically how to transform the current global value chain into a net-zero economy? As there is a gap in the current funding requirements, we need to prioritize financial investments and narrow the definition of the eligible investment universe. As a result, the investment processes of the core and satellite portfolios are very different. The core portfolio is more of a top-down allocation process and exclusion strategy, where the central climate risk metric is carbon intensity. The satellite portfolio is more of a bottom-up allocation process and asset selection strategy, where the central climate risk metric is green intensity. Finally, the risk assessment of the global core-satellite portfolio must be addressed, such as the level of tracking error volatility relative to a conventional benchmark (e.g., the 60/40 constant mix strategy) or a traditional strategic asset allocation.

Keywords: Net zero emissions, core-satellite strategy, decarbonization, transition, greenness, carbon intensity, green intensity, equity allocation, bond allocation, tracking error.

JEL Classification: G11, Q5.

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1 Introduction

The ESG landscape is undergoing profound change, with climate risk becoming increasingly important. In particular, net-zero emissions policies have gained significant traction in recent years with the proliferation of net-zero alliances[1] (GFANZ, NZAOA, NZAM, NZBA, etc.) and their commitments. In Barahhou *et al.* (2022), we defined the concept of net-zero and discussed in detail the implications for asset owners and managers. As mentioned in this first part, building a net-zero investment portfolio is more complex than building a decarbonized portfolio because the objective function includes at least two objectives: decarbonizing the portfolio and financing the transition. A first solution has already emerged and consists of changing the allocation process of low-carbon portfolios by introducing net-zero features, such as controlling the self-decarbonization of the strategy and improving the greenness of the portfolio. This first solution, called the comprehensive integrated approach, is very popular in the ETF markets and can be applied to a universe of corporate issuers (Barahhou *et al.*, 2022) or sovereign issuers (Barahhou *et al.*, 2023).

Table 1: Two building block approach

Decarbonizing the portfolio	**Financing the transition**
• Net-zero decarbonization portfolio	• Net-zero contribution portfolio
• Net-zero transition portfolio	• Net-zero funding portfolio
• Dynamic low-carbon portfolio	• Net-zero transformation portfolio

The comprehensive integrated approach can sometimes be difficult to implement because today, on average, carbon intensities are positively correlated with green intensities. This means that the greenness of the economy is not necessarily found in companies with low carbon footprints. Therefore, a second approach has emerged that is easier to implement, but more difficult to accept because it implies a significant departure from traditional benchmarks. It consists of adopting a core-satellite strategy in which decarbonization is applied to the core portfolio while the objective of the satellite portfolio is to finance the transition to a low-carbon economy. In the financial literature, the core portfolio is called the net-zero decarbonization portfolio, while the satellite portfolio is called the net-zero contribution portfolio, but other terms are used, as shown in Table 1. This is equivalent to splitting the problem into two sub-problems. The goal of the first sub-problem is to decarbonize and manage the carbon footprint of the investment. The goal of the second sub-problem is to contribute to increasing the green footprint of the economy.

This approach also has the advantage of making the allocation between the two net-zero policies clear. Of course, the allocation $\alpha(t)$ to the satellite can be dynamic and change over time as the world and economy progresses toward net-zero. Portfolio decarbonization has been studied extensively in Barahhou *et al.* (2022) and Le Guenedal and Roncalli (2022). We summarize the main findings here. First, decarbonization is an exclusion process. It will underweight companies and sectors with the highest carbon intensity. And sometimes this disinvestment turns into divestment. This is not always the philosophy of net-zero, because

[1] GFANZ = Glasgow Financial Alliance for Net-Zero, NZAOA = Net Zero Asset Owner Alliance, NZAM = Net Zero Asset Managers initiative, NZBA = Net Zero Banking Alliance.

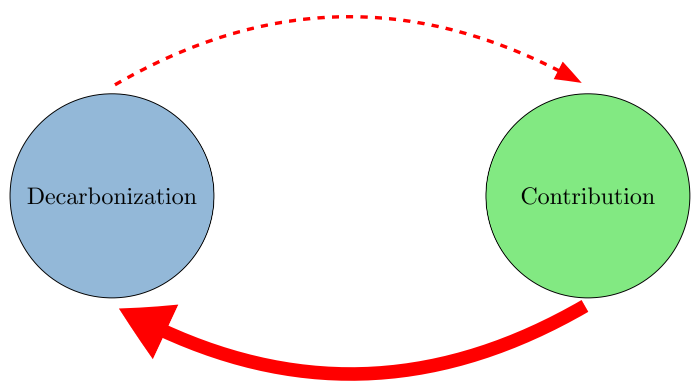
Table 2: The core-satellite approach

Decarbonized portfolio		Contribution portfolio
• Carbon intensity • Decarbonization pathway	+	• Green intensity • Financing the transition
• Top-down approach • Portfolio construction • Net-zero **carbon** metrics		• Bottom-up approach • Security selection • Net-zero **transition** metrics
$\mathbf{1-\alpha(t)}$		$\boldsymbol{\alpha}\mathbf{(t)}$

the underlying idea is to transform the brown elements of the economy into green elements. This applies to production processes, but also to companies. That's why engagement is an important tool to support decarbonization. Most often, divestment is associated with a sense of failure and its impact on corporate governance is unproven. The second finding is that portfolio decarbonization is a strategy that is long financials and short energy, materials and utilities. The case of utilities is problematic because this is the sector that is essential to achieving net-zero. The final lesson is that moving too fast can put investors at great risk in terms of tracking error, liquidity and diversification. The construction of the core portfolio is very close to the approach developed by Barahhou *et al.* (2023), and the previous findings remain valid. Nevertheless, we introduce the concept of a decarbonization sequence, which means that timing is an important factor. As explained by IEA (2021), the power sector must go green first, followed by buildings, then transport and industry. This means that utilities will have to decarbonize first and that 90% of this sector will have to be green by 2035. That's not a lot of time, just over 10 years. Therefore, portfolio decarbonization and engagement efforts must focus on this sector in the coming years. This also means that drastically reducing our allocation to this sector is not the optimal solution. We need to be selective and proactive, and we can use a specific decarbonization pathway for this sector rather than a global decarbonization pathway.

Building the satellite portfolio requires a deep understanding of how to achieve net-zero by 2050. It is important to know the production processes of goods and services, the constraints and the opportunities that a net-zero economy imposes or offers. Surely the biggest challenge is to analyze the current global value chain, to assess what a net-zero value chain is or must be by 2050, and to determine the transformation path between these two visions of the world. Today, the current global value chain is dominated by a central upstream node, the traditional energy sector, consisting mainly of oil, coal and gas (Desnos *et al.*, 2023). Tomorrow, when we reach net-zero emissions, the current global value chain will be dominated by electricity, which will have to be completely green. In short, we have to electrify the world, including developing countries, and the electricity has to be 100% green. By linking all industrial processes, including construction and transportation, to the power sector, more than 95% of global carbon emissions will be driven by the carbon intensity of electricity. And making electricity green will dramatically reduce its carbon intensity to below 20 gCO_2e per KWh. This is enough to allow the remaining anthropogenic CO_2 emissions to be removed from the atmosphere through carbon sinks, natural sequestration, and carbon sequestration. While simple on paper, the challenges are immense. For example, it means building 130 million kilometers of additional power grids and increasing electricity production by at least four times Energy Transitions Commission (2023a). We also need to produce more minerals such as aluminium, copper and zinc, and rare elements such as lithium and neodymium. Other challenges relate to the carbon efficiency of buildings, carbon capture technologies, hydrogen, sustainable agriculture, transportation, water management, etc. All of these requirements imply a huge cost associated with the net-zero transition, approximately $3.5 trillion per year (McKinsey, 2022). In such a critical situation, the question of financing becomes central, and investors are part of the answer. As the International Energy Agency has stated, financing the transition must be the number one priority (IEA, 2021). Because financing today helps decarbonize the economy tomorrow and faster, while it is not certain that decarbonizing the portfolio today will create this positive feedback loop between the carbon footprint of finance and the carbon footprint of the economy (Figure 1).

Figure 1: Decarbonisation and financing linkages



The analysis of the net-zero emissions scenario helps to define the investment universe of the satellite portfolio. Identifying the assets that are suitable for the satellite portfolio is an essential step. It is better to have a narrow specification of the eligible investment universe in order to invest in the most impacting securities. The distinction between bonds and stocks must be made because debt and equity do not have the same status and priority in the net-zero journey. The identification of satellite bonds goes beyond green bonds and can be extended to the GSS+ segment. Investing in green equities is more challenging as it requires a definition of green intensity. However, the EU taxonomy can help. These different aspects show that the construction of the satellite portfolio is specific and definitely a bottom-up process (Table 2).

This research paper is organized as follows. In Section Two, we focus on the core portfolio. We first study the decarbonization policy and then define the different portfolio constructions. We highlight the importance of self-decarbonization and present empirical results for both core equity and bond portfolios. In a second step, we assess the implications of portfolio decarbonization for strategic asset allocation. In particular, we propose the use of the Black-Litterman framework to value implied bets and measure implied risk premia. Section Three is devoted to the satellite portfolio and consists of two parts. The first part examines how to achieve net-zero emissions. We discuss funding, material and resource requirements, analyze the key sectors for net-zero, propose a narrow definition of the satellite investment portfolio, and show how to track net-zero progress. The second part focuses on the portfolio construction of the satellite strategy. We consider green bonds, green equities, sustainable infrastructure, and sustainable real estate. The estimation of the active risk of the core/satellite portfolio is presented in Section Four. Finally, Section Five provides some concluding remarks.

2 The core portfolio

In this section, we consider several implementations of the core portfolio. We recall that the objective of this portfolio is to follow the decarbonization pathway in order to achieve the transition to a low-carbon economy. In this case, the carbon intensity of the portfolio is the key metric to manage. The investor must therefore define his decarbonization strategy.

2.1 Decarbonization policy

The decarbonization policy consists of two elements. The first one is the decarbonization path of the investment portfolio, while the second item is the implementation model or the portfolio construction. Thus, the core portfolios of two investors with the same strategic asset allocation and the same decarbonization pathway may differ because they do not choose the same implementation strategy.

2.1.1 Decarbonization pathway

A decarbonization scenario is defined as the function that relates a decarbonization rate to a time index t:

$$\begin{aligned} f \quad : \quad & \mathbb{R}^+ \longrightarrow [0,1] \\ & t \longmapsto \boldsymbol{\mathcal{R}}(t_0, t) \end{aligned}$$

where t_0 is the base year and $\boldsymbol{\mathcal{R}}\left(t_0^-, t_0\right) = 0$. Generally, we assume that $\boldsymbol{\mathcal{R}}(t_0, t)$ is a non-decreasing function of time t. When considering a decarbonization pathway, we need to distinguish between two different concepts: economic decarbonization and financial decarbonization. In the first case, the variable of interest is the level of carbon emissions, while in the second case we use carbon intensity. Figure 46 on page 68 shows the Net Zero Emissions by 2050 (NZE) scenario provided by the International Energy Agency. This is a normative scenario based on a number of assumptions about the global energy sector. From this scenario, we can calculate the decarbonization path of the real economy and the different sectors. Figure 2 compares these with those used by the CTB and PAB benchmarks. It is clear that we are not comparing apples with apples. In fact, in the case of the real economy, the carbon emissions $\boldsymbol{\mathcal{CE}}(t)$ are assumed to follow the following trajectory:

$$\boldsymbol{\mathcal{CE}}(t) = \left(1 - \boldsymbol{\mathcal{R}}(t_0, t)\right) \boldsymbol{\mathcal{CE}}(t_0)$$

while we have for the PAB and CTB pathways:

$$\boldsymbol{\mathcal{CI}}(t) = (1 - \Delta\boldsymbol{\mathcal{R}})^{t-t_0} \left(1 - \boldsymbol{\mathcal{R}}^-\right) \boldsymbol{\mathcal{CI}}(t_0)$$

where $\Delta\boldsymbol{\mathcal{R}} = 7\%$ and $\boldsymbol{\mathcal{R}}^-$ takes the values 30% (CTB) and 50% (PAB) respectively (European Commission, 2020). By construction, the reduction path expressed in terms of carbon intensity has to be lower than the reduction path expressed in terms of carbon emissions. This observation raises the question of the magnitude of the reduction rate. Let us assume that the base date is 2020. The Paris-Aligned benchmarks imply a reduction rate of 65% by 2025 and 75% by 2030. This is much higher than the reduction rates proposed by the International Energy Agency, which are around 15% and 40% by 2025 and 2030 respectively. By comparison, the NZ frameworks for asset owners[2] propose a reduction rate of around 30% by 2025 and 50% by 2030 — see next section for more information and statistics. The AO curve corresponds to this average asset owner trajectory.

Figure 2: IEA, AO, CTB and PAB decarbonization pathways

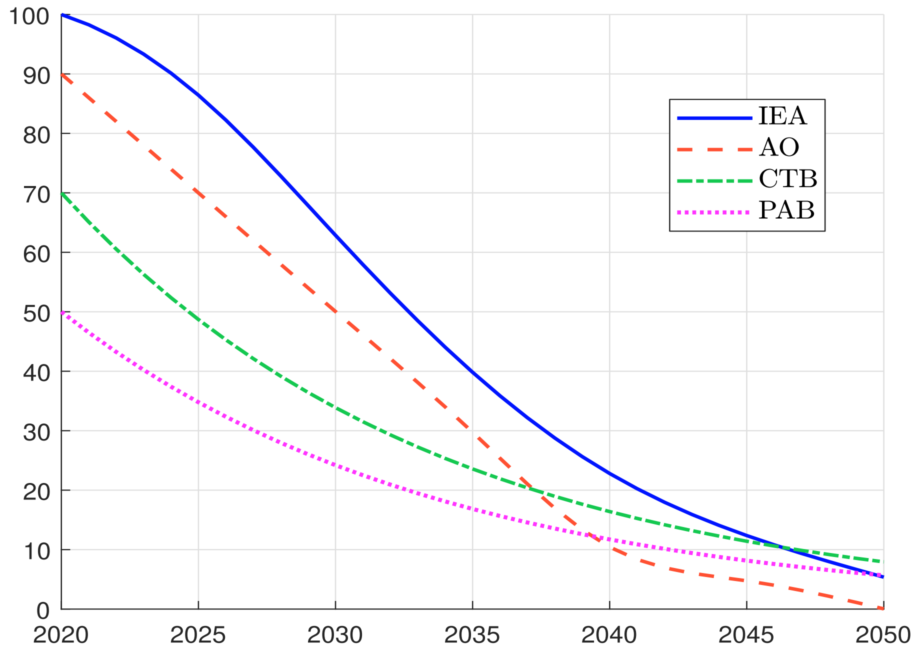
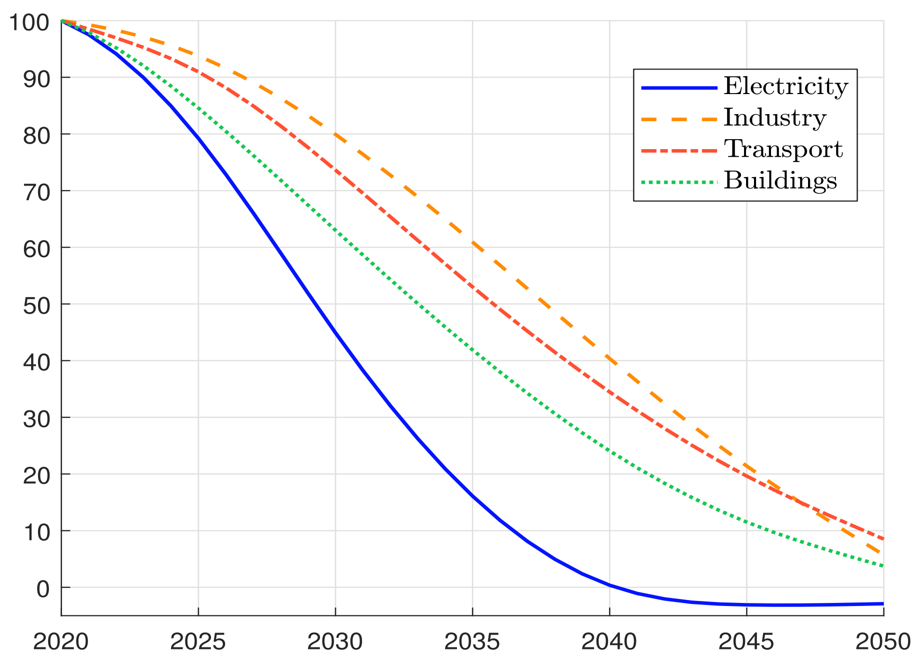


Figure 3: Sectoral decarbonization pathways



The previous analysis considered a global path for the whole economy. However, Figure 46 on page 68 shows that not all sectors are the same. In particular, three main sectors are affected (buildings, electricity and transport), while some sectors are "*hard-to-abate*" such as materials, steel, cement, petrochemicals, etc. Therefore, a net-zero investment policy must focus on these sectors, which means that we must not spend too much effort on some sectors, such as health care or communication services[3]. There is also a sequencing of decarbonization across sectors as shown in Figures 3 and 5. The order is as follows:

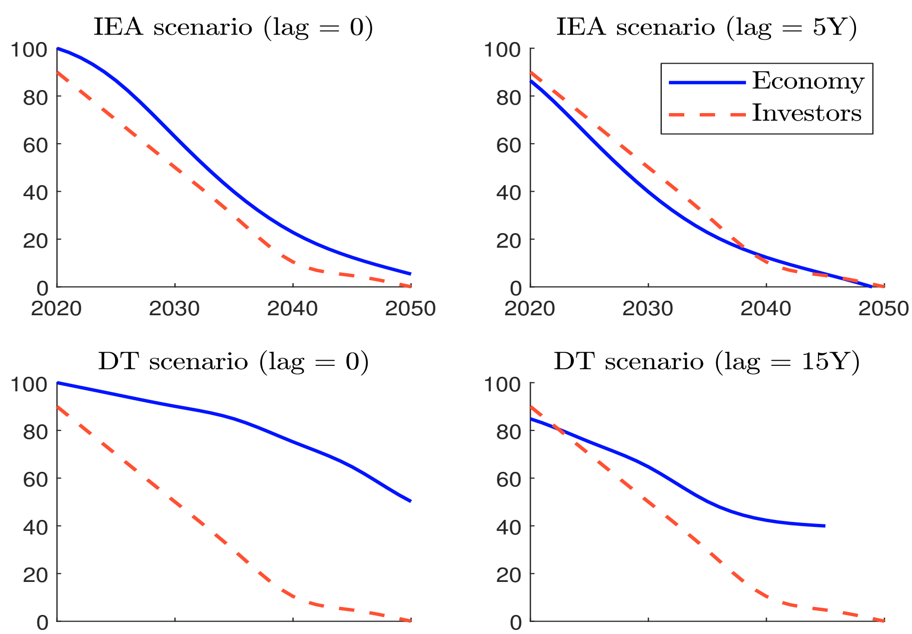
$$\text{Electricity} \succ \text{Buildings} \succ \text{Transport} \succ \text{Industry}$$

The timing of key technology transitions is the biggest constraint to achieving net-zero by 2050, according to all studies (IEA, 2021, 2023; McKinsey, 2022; Victoria *et al.*, 2022):

> "*All the paths entail similar technological transformations, but the timing of the scale-up of important technologies like electrolysis, carbon capture, and hydrogen network differs. Solar PV and onshore and offshore wind become the cornerstone of a net-zero energy system, enabling the decarbonization of other sectors via direct electrification (heat pumps and electric vehicles) or indirect electrification (using synthetic fuels)*" (Victoria *et al.*, 2022, page 1066).

The aim is to have almost 100% green electricity by 2035, otherwise the chances of meeting the target are very low. For instance, the industrial sector is the last critical sector to decarbonize, because it first needs green electricity, green materials, green buildings and green transport. The speed of decarbonization will then vary from sector to sector. In this context, we can ask whether it is appropriate to consider a global decarbonization pathway or different sectoral decarbonization pathways.

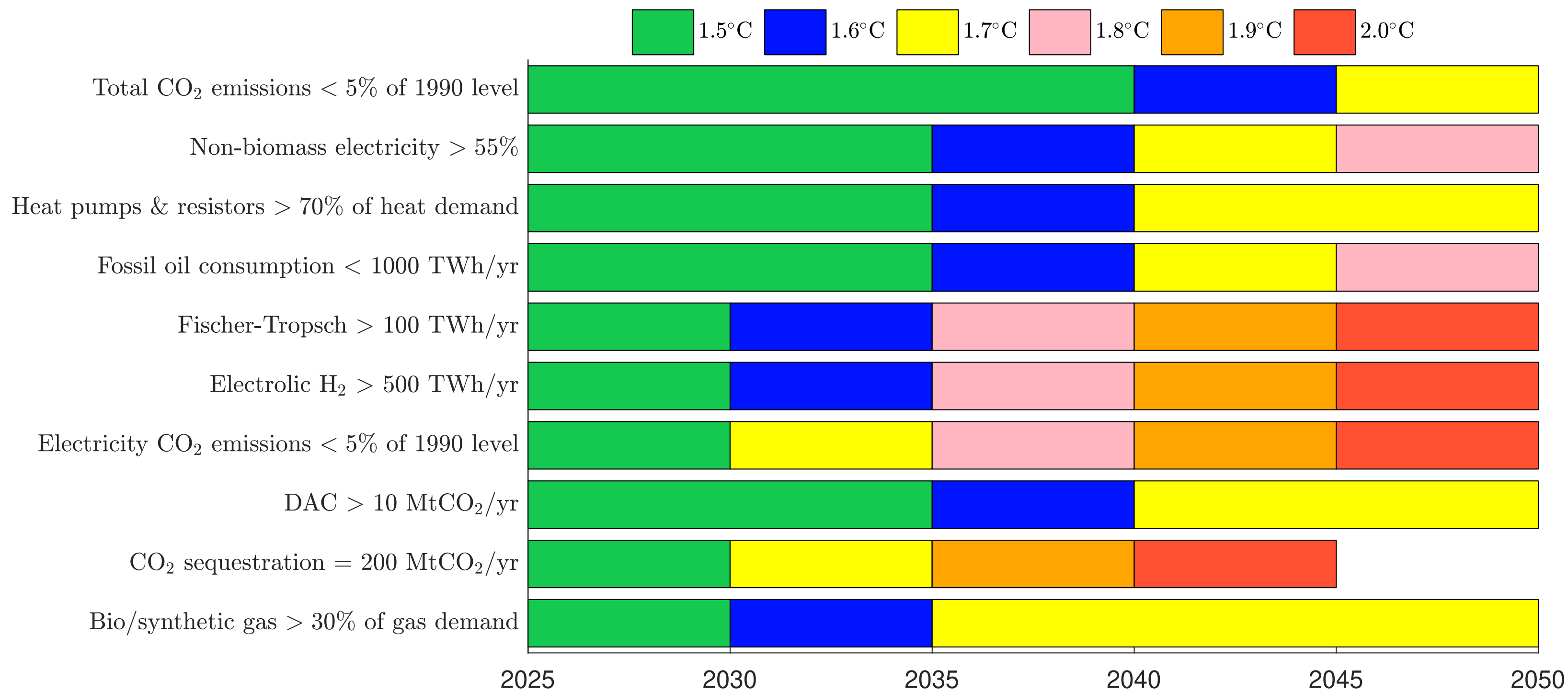
Figure 4: Timing alignment between economy and investor decarbonisation pathways



[2] The two main net-zero frameworks for asset owners are the Net Zero Asset Owners Alliance (NZAOA) and Paris Aligned Asset Owners (PAAO).

[3] Although these sectors must participate, they represent only a small part of the problem.

Figure 5: Key transformations occurring for different carbon budgets in Europe



The bars indicate the timeframe in which key technological transformations (described by labels on the left) occur for the modelled transition paths under carbon budgets corresponding to a temperature increase between 1.5°C and 2°C. Where the bar corresponding to one carbon budget is obscured by a different colour, this indicates that the timing of the technological transition is the same for both budgets.

Source: Victoria *et al.* (2022, Figure 3, page 1070).

The mismatch between the decarbonisation path of the economy and the decarbonisation path of the investor is critical. In the first panel of Figure 4, we show the previous IEA and AO decarbonization paths. We note that the mismatch can be measured as the time it takes for the reference pathway to achieve the same level of decarbonization than the pathway chosen by the investor. We have:

$$D(t) = \inf \left\{ h \in \mathbb{N} : \boldsymbol{\mathcal{R}}^{\star}(t_0, t+h) \geq \boldsymbol{\mathcal{R}}(t_0, t) \right\}$$

where $D(t)$ is the matching duration expressed in years, $\boldsymbol{\mathcal{R}}^{\star}(t_0, t)$ is the reference pathway and $\boldsymbol{\mathcal{R}}(t_0, t)$ is the investor pathway. For example, if $D(t)$ is equal to ten years, this means that the investor is ten years ahead of the economy. In the second panel of Figure 4, we apply a lag of four years to the NZE IEA scenario. As the curve coincides with the AO curve, we conclude that the asset management industry is four years ahead. The third panel presents an alternative scenario in which the transition to a low-carbon economy is delayed (DT scenario). In this case, we note that the matching duration in 2025 is longer than fifteen years. The exact values are given in Table 3.

Table 3: Matching duration in years

	$t = 2025$		$t = 2030$	
	IEA	DT	IEA	DT
AO	4	18	3	21
CTB	8	26	7	34
PAB	12	39	10	39

The previous analysis shows that it is important to monitor the gap between the decarbonization pathways of the economy and investors. We can assume that it is acceptable to be five years ahead, because the financial sector is always one step ahead of the economic cycle and is an important layer in accelerating the transition. But to be ten or fifteen years ahead is a huge financial risk for investors. Therefore, investors need to take into account the decarbonization pathway of the real economy and adjust their own decarbonization path by imposing a maximum matching period. Otherwise, they may find that their net-zero investment portfolios are disconnected from the economy, or that they are taking big bets on transition risk.

2.1.2 Investment universe

Specifying the eligible investment universe is the second component of a net-zero investment policy. Do we only consider public equities, do we need to expand the eligible assets to include sovereign bonds, what real assets can be added? The answers to these questions are not all obvious. For example, there is a consensus that climate risks are very important to a shareholder because ESG risks can affect the long-term business risk, and then they can have a big impact on the value of stocks. For a bondholder, the main concern is managing default risk, which is a more short-term risk (typically one or two years). And this concern increases with the credit risk of the corporate bond. Therefore, climate and extra-financial risks are of secondary importance for high-yield bonds. Theoretically, it is generally accepted that shareholders are more sensitive to climate and ESG factors than bondholders. Nevertheless, the corporate bond market is key to financing the transition. From an impact investing perspective, bondholders have more influence on capital allocation than shareholders. Therefore, net-zero investing concerns both listed equities and corporate bonds. Other assets can also be considered (ILN, 2022). In particular, net-zero investing must apply to some real assets, such as real estate and infrastructure. Few asset owners also include private debt and private equity, but without an explicit benchmark it is difficult to define a baseline scenario for these two specific markets.

Table 4: Net-zero targets of NZAOA members

Year	Statistic	Equity	Credit	Real estate	Infrastructure	Portfolio	Total
2025	Frequency	70.7%	67.2%	39.7%	3.4%	24.1%	84.1%
	Average level	25.6%	25.8%	23.4%	11.8%	27.6%	25.2%
2030	Frequency	81.8%	72.7%	54.5%	18.2%	9.1%	15.9%
	Average level	50.9%	49.8%	43.2%	50.0%	50.0%	48.7%

Source: NZAOA (2023), www.unepfi.org/net-zero-alliance/resources/member-targets & Authors' calculations.

We have collected the members' intermediate targets of the Net Zero Asset Owner Alliance. As of May 2023, 69 members published targets in line with the NZAOA commitment. A summary of these targets is shown in Table 4. 84.1% of asset owners have set a target date of 2025, while 15.9% prefer to consider a target date of 2030. Of those with a 2025 target date, 24.1% have set a global target for their entire portfolio without distinguishing between asset classes, 70.7% have set a specific target for their equity portfolios, 67.2% for their global bond portfolios, 39.7% for their real estate investments and only 3.4% for their infrastructure assets. The average global target is 25.2%, which is slightly lower than the recommended 30%. Looking ahead to 2030, this figure is 48.7%, which is in line with the recommended level of 50%.

Table 5: Net-zero targets of NZAM members

	Total	IPE 500	Other	IPE 500	Other
Number of asset managers	316	127	189	40.2%	59.8%
Disclosed targets	228	103	125	45.2%	54.8%
Net-zero assets	\$16.5 tn	\$13.4 tn	\$3.06 tn	46.5%	69.3%

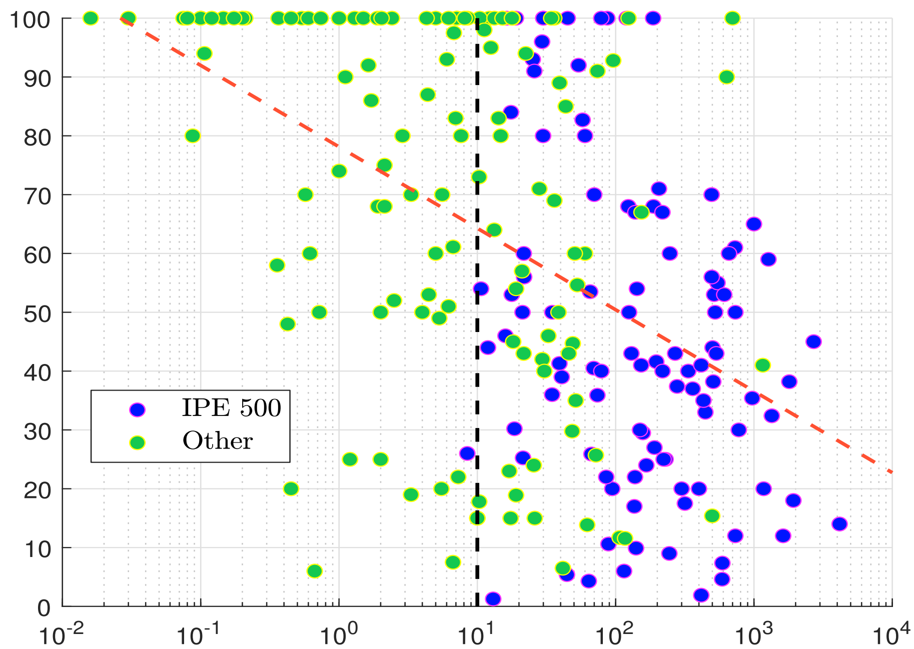
Source: NZAM (2023), www.netzeroassetmanagers.org & Authors' calculations.

Let us consider the net-zero commitments of members of the Net Zero Asset Managers (NZAM) initiative. At the end of June 2023, there are 316 signatories representing \$60 tn in assets under management (Table 5). Of these asset managers, 127 are ranked in the IPE TOP 500, *i.e.* 40% of the signatories. If we focus on the 228 asset managers that have published their net-zero targets, the average coverage ratio is equal to 46.5% and 69.3% of assets under management for the IPE TOP 500 and other asset managers respectively. This represents a total amount of \$16.5 tn or 27.5% of assets under management[4], which are committed to be managed in line with net-zero.

Figure 6 shows the announced percentage and the assets under management of the 228 disclosed targets. We note that some asset managers have the ambition to move 100% of their assets to net-zero investments. However, these are small asset managers and pure players. If we look at large asset managers, the ratio is generally below 40%. This is why we observe a decreasing function between assets under management and the percentage of net-zero commitments. One implication is that the net-zero policy does not generally affect

[4]This figure is calculated by dividing the announced amount (\$16.5 tn) by the total assets under management (\$60 tn). If we restrict the analysis to assets managers that have disclosed their net-zero policy, the ratio is 38.7% of AUM.

Figure 6: Scatterplot between assets under management and initial commitment in %



Source: NZAM (2023), www.netzeroassetmanagers.org & Authors' calculations.

100% of assets. The definition of the perimeter of the investment universe that must be net-zero is therefore an important element of the net-zero policy. Table 6 shows the number and average level of objectives. As in the case of asset owners, we see that most of the targets relate to the global portfolio without distinguishing between asset classes. When targets refer to asset classes, they mainly cover equity or credit portfolios, and to a lesser extent real estate. There are several explanations for this:

- The liquidity of the investment universe is an important factor. Transforming a conventional portfolio into a net-zero portfolio requires a liquid investment universe. Otherwise, the cost may be prohibitive. This means that it is easier to buy and sell assets in the equity market and to manage the turnover of the stock portfolio.

- Primary market flows help to implement a net-zero investment policy. In this case, new investments can be directed towards fulfilling the obligations of the policy.

- We observe that very few investors define net-zero rules for sovereign bonds. The risk is certainly too high to distort the allocation in terms of market exposure and liquidity profile.

Table 6: Net-zero targets of NZAM members

Year	Equity	Credit	Real estate	Infrastructure	Portfolio
2025	31.0% (6)	33.3% (4)	28.5% (3)	28.0% (2)	30.7% (24)
2030	54.1% (7)	51.7% (6)	53.3% (3)	40.0% (2)	51.7% (128)
Global	42.6% (13)	42.5% (10)	40.9% (6)	34.0% (4)	41.2% (152)

Source: NZAM (2023), www.netzeroassetmanagers.org & Authors' calculations.

2.1.3 Portfolio strategy

Optimization strategy At first glance, the objective function seems simple to define. We want to build a core portfolio that follows the decarbonization pathway and has minimum active risk relative to the strategic asset allocation defined by the investor. As shown by Barahhou *et al.* (2022), this objective function is not fully consistent with a net-zero policy. First, we need to make a clear distinction between a low-carbon portfolio and a net-zero portfolio. In the former case, we want to reduce the carbon footprint of a given portfolio at a given time. A low-carbon portfolio is therefore a static approach to decarbonization. A net-zero portfolio implies a dynamic approach to decarbonization to achieve net-zero by 2050. So the concept of self-decarbonisation is important. In this context, we cannot think of a net-zero portfolio as an investment process where we just apply a series of decarbonization rates. In a sense, decarbonisation will have to become partly endogenous.

Let us illustrate the previous issue with an example. The baseline carbon intensity is equal to 100 tCO_2e/\$ mn. Suppose the target decarbonization rate is equal to 30% in January 2023 and 35% in January 2024. At the end of December 2023, we may face several situations. The carbon footprint of the portfolio is greater than 70 tCO_2e/\$ mn. This is the worst situation because we start the year with a carbon intensity of 70 tCO_2e/\$ mn and end the year with a higher carbon intensity. The only solution is then to rebalance the portfolio at the end of December 2023 to achieve a carbon footprint below 65 tCO_2e/\$ mn. The second case corresponds to a situation where the carbon footprint of the portfolio is between 65 and 70 tCO_2e/\$ mn. The portfolio has decarbonized itself during 2023, but not enough to meet the target. Again, we rebalance the portfolio at the end of December 2023 to achieve a carbon intensity of 65 tCO_2e/\$ mn. The third case is the best situation, as the decarbonization rate of the portfolio is greater than 35% at the end of December 2023. We do nothing. Following a decarbonization path can then be explained by two factors. The first is the rebalancing process. In theory, a decarbonization path can always be achieved by rebalancing the portfolio. In this approach, the decarbonization pathway of the net-zero investment is not due to the dynamics of asset decarbonization, and issuers's efforts to address climate change. The second factor is the self-decarbonization of the portfolio. In this approach, a part of the decarbonization pathway of the net-zero investment is endogenous.

Following Barahhou *et al.* (2022), we define $\boldsymbol{\mathcal{CI}}(t, x; \mathcal{F}_s)$ as the carbon intensity of Portfolio x calculated at time t with the information $\mathcal{F}_s$ available at time s. The decarbonization rate between time t and $t+1$ is equal to:

$$\boldsymbol{\mathcal{R}}(t, t+1) = \frac{\boldsymbol{\mathcal{CI}}\left(t, x(t); \mathcal{F}_t\right) - \boldsymbol{\mathcal{CI}}\left(t+1, x(t+1); \mathcal{F}_{t+1}\right)}{\boldsymbol{\mathcal{CI}}\left(t_0, b(t_0); \mathcal{F}_{t_0}\right)}$$

The variation $\boldsymbol{\mathcal{CI}}\left(t, x(t); \mathcal{F}_t\right) - \boldsymbol{\mathcal{CI}}\left(t+1, x(t+1); \mathcal{F}_{t+1}\right)$ between two rebalancing dates can be split into two components:

1. a self-decarbonization $\boldsymbol{\mathcal{CI}}\left(t, x(t); \mathcal{F}_t\right) - \boldsymbol{\mathcal{CI}}\left(t+1, x(t); \mathcal{F}_{t+1}\right)$ of Portfolio $x(t)$ between t and $t+1$ and;

2. a rebalancing decarbonization $\boldsymbol{\mathcal{CI}}\left(t+1, x(t); \mathcal{F}_{t+1}\right) - \boldsymbol{\mathcal{CI}}\left(t+1, x(t+1); \mathcal{F}_{t+1}\right)$ measuring the change in carbon footprint variation from Portfolio $x(t)$ to Portfolio $x(t+1)$ at time $t+1$.

Finally, we have:

$$\begin{aligned}\boldsymbol{\mathcal{R}}(t,t+1) &= \frac{\boldsymbol{\mathcal{CI}}\left(t,x(t);\mathcal{F}_t\right)-\boldsymbol{\mathcal{CI}}\left(t+1,x(t);\mathcal{F}_{t+1}\right)}{\boldsymbol{\mathcal{CI}}\left(t_0,b(t_0);\mathcal{F}_{t_0}\right)}+ \\ &\quad \frac{\boldsymbol{\mathcal{CI}}\left(t+1,x(t);\mathcal{F}_{t+1}\right)-\boldsymbol{\mathcal{CI}}\left(t+1,x(t+1);\mathcal{F}_{t+1}\right)}{\boldsymbol{\mathcal{CI}}\left(t_0,b(t_0);\mathcal{F}_{t_0}\right)} \\ &= \boldsymbol{\mathcal{SDR}}(t,t+1)+\boldsymbol{\mathcal{RDR}}(t,t+1)\end{aligned}$$

where $\boldsymbol{\mathcal{SDR}}(t,t+1)$ and $\boldsymbol{\mathcal{RDR}}(t,t+1)$ are the self-decarbonization and rebalancing decarbonization ratios.

We consider an example with five stocks. To compute the covariance matrix Σ, we assume that the beta coefficients are equal to 0.90, 1.25, 0.78, 1.17 and 1.24, the idiosyncratic volatilities are equal to 5%, 6%, 4%, 3% and 7% and the market volatility equals 20%. The benchmark b is the equally-weighted portfolio. We have the following carbon intensities:

Asset	#1	#2	#3	#4	#5
$\boldsymbol{\mathcal{CI}}_i(t_0)$	50	75	100	150	500
$\boldsymbol{\mathcal{CI}}_i(t)$	49	73	97	140	490
$\boldsymbol{\mathcal{CI}}_i(t+1)$	48	80	98	145	440

We are targeting decarbonization levels of 30% and 34% at time t and $t+1$. Following Barahhou *et al.* (2022), the optimal portfolio is the solution of the following optimization problem:

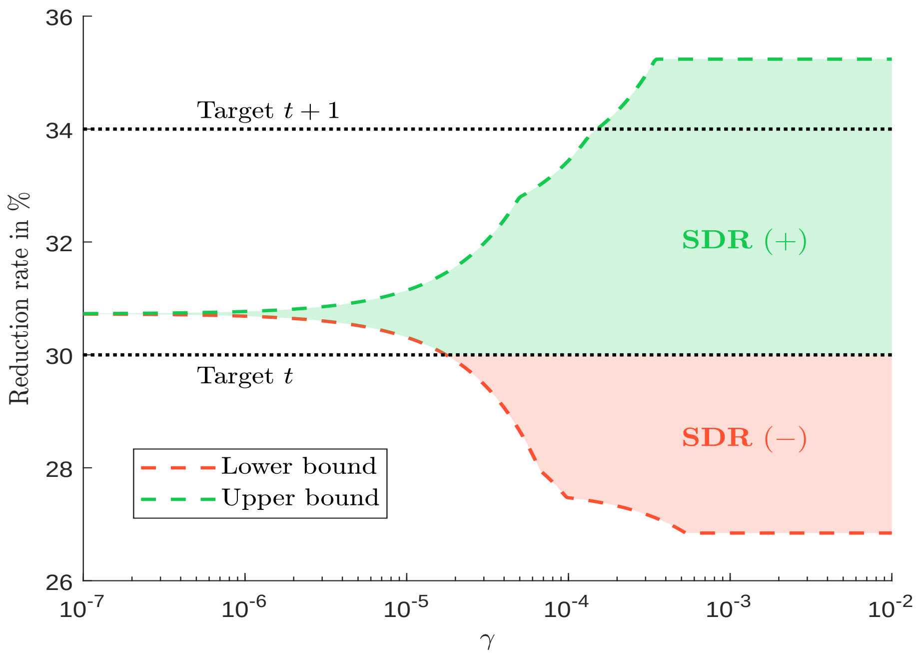
$$\begin{aligned}x(t) &= \arg\min \frac{1}{2}(x-b)^\top \Sigma (x-b) \\ &\text{s.t.} \quad \begin{cases}\mathbf{1}_n^\top x = 1 \\ \boldsymbol{\mathcal{CI}}(t)^\top x \leq \left(1-\boldsymbol{\mathcal{R}}(t_0,t)\right)\boldsymbol{\mathcal{CI}}(t_0,b,\mathcal{F}_{t_0}) \\ \mathbf{0}_n \leq x \leq \mathbf{1}_n\end{cases}\end{aligned}$$

Therefore, we minimize the variance of the tracking error relative to the benchmark under the constraint of carbon intensity reduction. Since we have $\boldsymbol{\mathcal{CI}}(t_0,b,\mathcal{F}_{t_0})=175$, the optimal portfolio $x(t)$ is $\left(24.14\%,25.15\%,18.38\%,23.98\%,8.35\%\right)$ and the tracking error volatility is 92.4 bps. We notice that $\boldsymbol{\mathcal{CI}}\left(t,x(t);\mathcal{F}_t\right)=122.50$ and $\boldsymbol{\mathcal{CI}}\left(t+1,x(t);\mathcal{F}_{t+1}\right)=121.23$. We check that $\boldsymbol{\mathcal{R}}(t_0,t)=30\%$ and deduce that $\boldsymbol{\mathcal{SDR}}(t,t+1)=0.73\%$, which is lower than $\boldsymbol{\mathcal{R}}(t,t+1)=4\%$. From time t to $t+1$, Portfolio $x(t)$ has decarbonized itself, but not enough to reach the target of 34% at time $t+1$. This means that we need to rebalance the portfolio at time $t+1$. Let us assume that we know the carbon intensity vector at time $t+1$. The optimal solution is to find the portfolio such that $\boldsymbol{\mathcal{CI}}(t)^\top x \leq \left(1-\boldsymbol{\mathcal{R}}(t_0,t)\right)\boldsymbol{\mathcal{CI}}(t_0,b,\mathcal{F}_{t_0})$ and $\boldsymbol{\mathcal{CI}}(t+1)^\top x \leq \left(1-\boldsymbol{\mathcal{R}}(t_0,t+1)\right)\boldsymbol{\mathcal{CI}}(t_0,b,\mathcal{F}_{t_0})$. We obtain $x(t)=\left(25.56\%,26.11\%,17.94\%,23.37\%,7.02\%\right)$. In this case, we check that $\boldsymbol{\mathcal{R}}(t_0,t+1)$ $=34\%$, but $\boldsymbol{\mathcal{R}}(t_0,t)$ is equal to 33.7%. This portfolio has a tracking error volatility of 105.1 bps, which is higher than the previous figure. In fact, we can find many non-optimal portfolios that satisfy the constraints $\boldsymbol{\mathcal{R}}(t_0,t)\geq 30\%$ and $\boldsymbol{\mathcal{R}}(t_0,t+1)\geq 34\%$. Another approach is to consider the following optimization problem:

$$\begin{aligned}x(t;\gamma,\epsilon) &= \arg\min \frac{1}{2}(x-b)^\top \Sigma (x-b)+\epsilon\gamma x^\top \boldsymbol{\mathcal{CI}}(t+1) \\ &\text{s.t.} \quad \begin{cases}\mathbf{1}_n^\top x = 1 \\ \boldsymbol{\mathcal{CI}}(t)^\top x \leq \left(1-\boldsymbol{\mathcal{R}}(t_0,t)\right)\boldsymbol{\mathcal{CI}}(t_0,b,\mathcal{F}_{t_0}) \\ \mathbf{0}_n \leq x \leq \mathbf{1}_n\end{cases}\end{aligned}$$

where $\gamma > 0$. We face a trade-off between the tracking error risk minimization and the self-decarbonization constraint. When ϵ is set to $+1$, we obtain the upper bound while the lower bound is determined when $\epsilon = -1$. Figure 7 shows the self-decarbonization range, which is bounded by two areas: the positive SDR region ($\boldsymbol{\mathcal{SDR}}(t, t+1) \geq 0$) and the negative SDR region ($\boldsymbol{\mathcal{SDR}}(t, t+1) \leq 0$).

Figure 7: Lower and upper bound of the self-decarbonization area



In practice, we do not know at time t the values of the carbon intensity that will be applied at time $t+1$. The computation of the self-decarbonization ratio can only be done ex-post. Nevertheless, it does not mean that we can not include a self-decarbonization constraint in the core portfolio. The underlying idea is to estimate the value of $\boldsymbol{\mathcal{SDR}}(t, t+1)$ and to add the constraint $\widehat{\boldsymbol{\mathcal{SDR}}}(t, t+1) \geq \boldsymbol{\mathcal{SDR}}^{\star}$. There are three main approaches to assessing the self-decarbonization of a portfolio:

1. The best known is the use of implied temperature ratings (Le Guenedal and Roncalli, 2022). The self-decarbonization constraint is replaced by a temperature constraint: $\mathrm{ITR}(x) = \sum_{i=1}^{n} x_i \, \mathrm{ITR}_i \leq \mathrm{ITR}^{\star}$ where ITR_i is the implied temperature rating of Issuer i and $\mathrm{ITR}^{\star}$ is the maximum acceptable threshold. As there is generally no time horizon for implied temperature ratings, this approach is more of a long-term solution.

2. The second method, based on the $\mathcal{PAC}$ framework developed in Le Guenedal *et al.* (2022), is a variant of the previous approach. In this case, we use a scoring system based on the net-zero metrics of participation, ambition and credibility.

3. The latter was proposed by Barahhou *et al.* (2022). We estimate the self-decarbonization of each issuer through its carbon momentum. We generally impose that:

$$\boldsymbol{\mathcal{CM}}(x) = \sum_{i=1}^{n} x_i \boldsymbol{\mathcal{CM}}_i(t) \leq \boldsymbol{\mathcal{CM}}^{\star} \tag{1}$$

where $\mathcal{CM}_i(t)$ is the carbon momentum of Issuer i and $\mathcal{CM}^\star$ is the negative target of the carbon momentum.

The constraint defined by Equation (1) may not always be relevant since it does not consider the magnitude of carbon intensities. The appropriate self-decarbonization constraint can be expressed as follows:

$$\widehat{\mathcal{CI}}(t+1)^\top x \leq \big(1 - \mathcal{R}(t_0,t) - \alpha\mathcal{R}(t,t+1)\big)\mathcal{CI}(t_0,b,\mathcal{F}_{t_0})$$

where $\widehat{\mathcal{CI}}(t+1)$ is the vector of expected carbon intensity and $\alpha \in [0,1]$. By construction, we can write $\widehat{\mathcal{CI}}_i(t+1) = \big(1 + \mathcal{CM}_i(t)\big)\mathcal{CI}_i(t)$, which implies that:

$$\Big(\big(\mathbf{1}_n + \mathcal{CM}(t)\big) \odot \mathcal{CI}(t)\Big)^\top x \leq \big(1 - \mathcal{R}(t_0,t) - \alpha\mathcal{R}(t,t+1)\big)\mathcal{CI}(t_0,b,\mathcal{F}_{t_0}) \qquad (2)$$

Our experience shows that it is better to use Equation (2) rather than Equation (1). In fact, this latter can be seen as a special case of the former one when carbon intensity is normalized. For instance, if $\mathcal{CM}_i(t) = -10\%$, the impact of the carbon momentum is greater for an issuer with a high carbon intensity (e.g., 1000) than for an issuer with a low carbon intensity (e.g., 50). Figure 8 illustrates the discrepancy between $\mathcal{CM}_i(t)$ and $\widehat{\mathcal{CI}}_i(t+1)$. In Equation (2), the impact of the carbon momentum is amplified by the current carbon intensity but also by the weight of Issuer i in the portfolio. We have:

$$\begin{aligned}
\mathcal{CI}\big(t+1,x(t),\mathcal{F}_t\big) - \mathcal{CI}\big(t,x(t),\mathcal{F}_t\big) &= \sum_{i=1}^n x_i(t)\,\widehat{\mathcal{CI}}_i(t+1) - \sum_{i=1}^n x_i(t)\,\mathcal{CI}_i(t) \\
&= \sum_{i=1}^n x_i(t)\,\mathcal{CI}_i(t)\,\mathcal{CM}_i(t) \\
&= \mathcal{CI}\big(t,x(t),\mathcal{F}_t\big)\sum_{i=1}^n \omega_i(t)\,\mathcal{CM}_i(t)
\end{aligned}$$

where $\omega_i(t) \propto x_i(t)\,\mathcal{CI}_i(t)$ is the carbon intensity contribution of the issuer i for Portfolio $x(t)$. The above relationship indicates that the self-decarbonization is mainly driven by issuers with the highest carbon momentum and/or carbon intensity contribution.

We recall that $\mathcal{CI}(t_0,b,\mathcal{F}_{t_0}) = 175$ and $\mathcal{CI}\big(t,x(t),\mathcal{F}_t\big) = 122.50$ for the benchmark and the optimal portfolio. We also have $\mathcal{CI}\big(t+1,x(t),\mathcal{F}_{t+1}\big) = 121.23$, which implies a self-decarbonization of 0.73% between t and $t+1$. Let us assume that the vector of carbon momentum is equal to $\big(-1\%, +1\%, -2\%, -2\%, -5\%\big)$. If we add the constraint defined by Equation (2) and set $\alpha = 50\%$, we obtain the following solution[5]:

$$x(t) = \big(41.20\%, 26.19\%, 13.77\%, 6.42\%, 12.42\%\big)$$

This portfolio has a tracking error volatility of 149 bps, while its self-decarbonization rate is equal to 2.47%. Improvement of this solution is possible, but we must be careful because the risk of tracking error can grow faster as illustrated in Figure 9. It is also clear that there is no solution if we aim for a high value of α (greater than 65% in our example).

[5] We impose that the carbon intensity reduction at time t is exactly 30%.

Figure 8: Equation (1) vs. Equation (2)

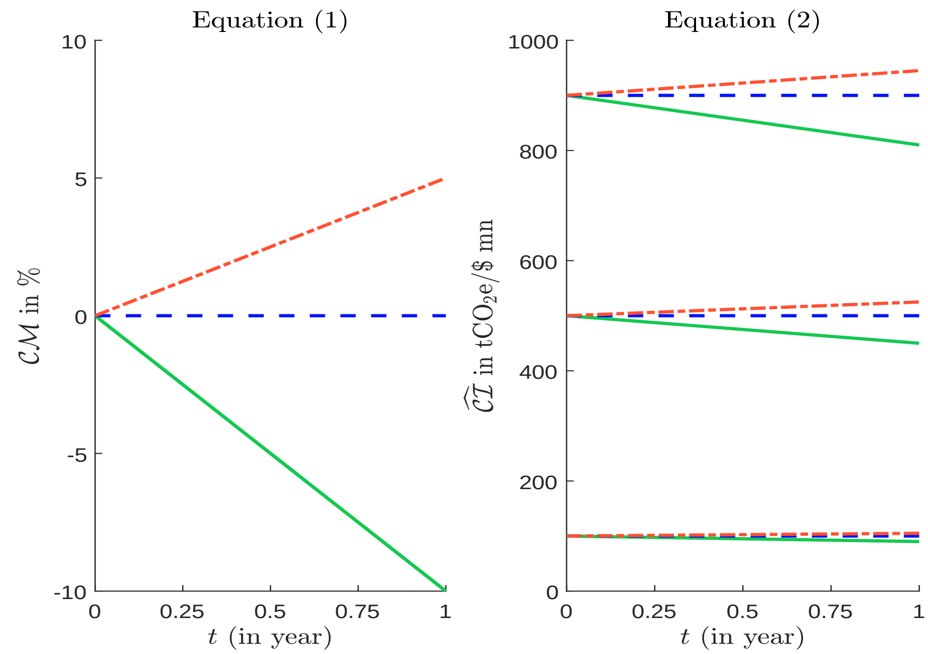
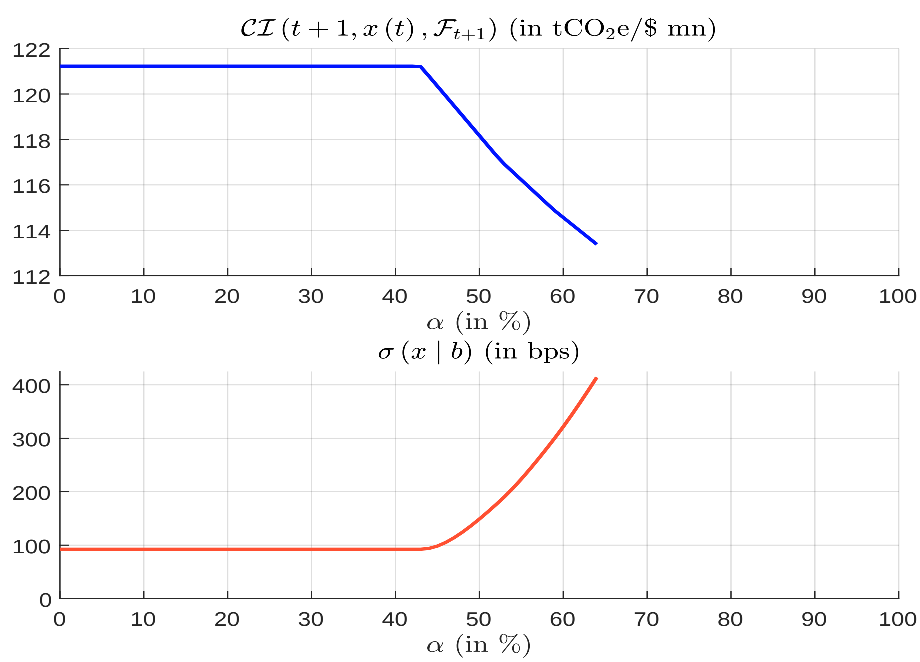


Figure 9: Relationship between α, $\mathcal{CI}\left(t+1, x\left(t\right), \mathcal{F}_{t+1}\right)$ and $\sigma\left(x\left(t\right) \mid b\right)$



Exclusion strategy As demonstrated by Barahhou *et al.* (2022), net-zero investing is an exclusion process. Therefore, instead of using an optimizer to remove assets from the portfolio, we can apply exclusion rules based on asset filtering. This approach has been proposed by Andersson *et al.* (2016) to construct low-carbon portfolios. The underlying idea is to exclude a certain fraction of securities and reallocate the proceeds of the exclusion to the selected securities. Following Roncalli (2023), we define a decarbonization score s_i for Asset i and the following preference ordering: $i \succ j \Leftrightarrow s_i \leq s_j$. This means that we prefer the assets with low scores over assets with high scores. For instance, we can set $s_i = \boldsymbol{\mathcal{CI}}_i$, which means that we want to exclude assets with high carbon intensities. Let $s_{i:n}$ be the i^{th} order statistic of $(s_1, \ldots, s_n)$ such that:

$$\min s_i = s_{1:n} \leq s_{2:n} \leq \cdots \leq s_{i:n} \leq \cdots \leq s_{n-1:n} \leq s_{n:n} = \max s_i$$

The score threshold $s^{(m,n)}$ is equal to $s^{(m,n)} = s_{n-m+1:n}$ where $s_{n-m+1:n}$ is the $(n-m+1)$-th order statistic of $(s_1, \ldots, s_n)$. Removing the m worst performing assets is equivalent to imposing the constraint: $s_i \geq s^{(m,n)} \Rightarrow x_i = 0$. We deduce that the proceeds of the exclusion φ are equal to:

$$\varphi = \sum_{i=1}^{n} b_i \mathbb{1}\left\{ s_i \geq s^{(m,n)} \right\}$$

A first solution is to reallocate φ proportionally to all assets remaining in the portfolio:

$$x_i = \left\{ \begin{array}{ll} 0 & \text{if } s_i \geq s^{(m,n)} \\ \dfrac{b_i}{1-\varphi} & \text{otherwise} \end{array} \right.$$

To find the net-zero portfolio corresponding to the decarbonization rate $\boldsymbol{\mathcal{R}}(t_0, t)$, we note $x^{(m,n)}$ the portfolio excluding m assets. The optimal portfolio is then defined as $x^{(m^\star,n)}$ where:

$$m^\star = \inf \left\{ m : \frac{\boldsymbol{\mathcal{CI}}\left(t_0, b\left(t_0\right)\right) - \boldsymbol{\mathcal{CI}}\left(t, x^{(m,n)}\right)}{\boldsymbol{\mathcal{CI}}\left(t_0, b\left(t_0\right)\right)} \geq \boldsymbol{\mathcal{R}}\left(t_0, t\right) \right\} \tag{3}$$

This is the approach proposed by Andersson *et al.* (2016) and Jondeau *et al.* (2021). A second solution is to reallocate the exclusion proceeds by minimizing the tracking error risk with respect to the benchmark:

$$\begin{aligned} x^{(m,n)} &= \arg\min \frac{1}{2}(x-b)^\top \Sigma (x-b) \\ &\text{s.t.} \left\{ \begin{array}{l} \mathbf{1}_n^\top x = 1 \\ \mathbf{0}_n \leq x \leq \mathbb{1}\left\{ s \geq s^{(m,n)} \right\} \end{array} \right. \end{aligned} \tag{4}$$

We use the previous rule (3) to find the optimal portfolio $x^{(m^\star,n)}$. An alternative solution is to impose the constraint $\boldsymbol{\mathcal{CI}}(t)^\top x \leq \left(1 - \boldsymbol{\mathcal{R}}(t_0, t)\right) \boldsymbol{\mathcal{CI}}\left(t_0, b, \mathcal{F}_{t_0}\right)$ in the optimization problem (4) (Bolton *et al.*, 2022).

Remark 1. *The choice of the decarbonization score depends on the objective function. A simple solution is to set s_i to the carbon intensity $\boldsymbol{\mathcal{CI}}_i(t)$. If we want to take into account the carbon momentum, we get:*

$$s_i = \widehat{\boldsymbol{\mathcal{CI}}}_i(t+1) = \left(1 + \boldsymbol{\mathcal{CM}}_i(t)\right) \boldsymbol{\mathcal{CI}}_i(t)$$

Mixing active and passive management The two previous strategies are suitable for passive management or for a strategic asset allocation of a large investor, whose neutral allocation is defined with respect to market capitalization indices. We have implicitly assumed that the asset selection is made within the benchmark universe at time t_0: $i \in b(t_0)$. Of course, we can remove this constraint and extend the strategies to an investment universe that differs from the reference benchmark. For example, the equity portfolio manager can construct a net-zero portfolio by investing a part of the fund in CTB/PAB equity indices and using active stock selection for the remaining part. We have $x(t) = \varpi x_1(t) + (1-\varpi)x_2(t)$ where $x_1(t)$ is the portfolio of PAB/CTB indices, $x_2(t)$ is the portfolio of stocks and $(\varpi, 1-\varpi)$ is the allocation vector. Since we have $\boldsymbol{\mathcal{R}}(t_0,t) = \varpi\boldsymbol{\mathcal{R}}_1(t_0,t) + (1-\varpi)\boldsymbol{\mathcal{R}}_2(t_0,t)$, we deduce that the target level for the second bucket is equal to:

$$\boldsymbol{\mathcal{R}}_2(t_0,t) = \frac{\boldsymbol{\mathcal{R}}(t_0,t) - \varpi\boldsymbol{\mathcal{R}}_1(t_0,t)}{1-\varpi}$$

For example, if $\varpi = 50\%$, $\boldsymbol{\mathcal{R}}(t_0,t) = 20\%$ and $\boldsymbol{\mathcal{R}}_1(t_0,t) = 30\%$, we need to target a reduction rate $\boldsymbol{\mathcal{R}}_2(t_0,t)$ of 10% for the stock selection. This gives the fund manager more freedom to select securities.

The case of bonds In the case of bonds, the tracking error volatility is not a relevant measure of risk. Therefore, we replace it with the active risk function proposed by Barahhou *et al.* (2022):

$$\mathcal{R}(x \mid b) = \varphi \underbrace{\sum_{s=1}^{n_{\mathcal{S}ector}} \left| \sum_{i\in s} (x_i - b_i) \cdot \mathrm{DTS}_i \right|}_{\text{DTS component}} + \underbrace{\frac{1}{2}\sum_{i\in b} |x_i - b_i|}_{\text{AS component}} + \underbrace{\mathbb{1}_{\Omega_{\mathrm{MD}}}(x)}_{\text{MD component}}$$

where DTS_i and MD_i are the duration-times-spread and modified duration factors, $\Omega_{\mathrm{MD}} = \left\{x : \sum_{i=1}^{n}(x_i - b_i)\cdot \mathrm{MD}_i = 0\right\}$ and $\mathbb{1}_\Omega(x)$ is the convex indicator function.

2.1.4 Empirical results

Equity portfolios Following Barahhou *et al.* (2022), we implement the optimization problem by imposing weight constraints relative to the benchmark at the security and sector level. This implies that $x \in \Omega(m_w^-, m_w^+, m_s^-, m_s^+)$ where:

$$\Omega(m_w^-, m_w^+, m_s^-, m_s^+) = \left\{ \forall i : m_w^- b_i \le x_i \le m_w^+ b_i \wedge \forall j : m_s^- \sum_{i\in\mathcal{S}_j} b_i \le \sum_{i\in\mathcal{S}_j} x_i \le m_s^+ \sum_{i\in\mathcal{S}_j} b_i \right\}$$

and $\mathcal{S}_j$ denotes the j^{th} sector. In particular, we consider two sets of constraints $\Omega(0,\infty,0,\infty) = \mathcal{C}_0$ and $\Omega(0,10,0.5,2) = \mathcal{C}_1$. $\mathcal{C}_0$ imposes no restrictions while $\mathcal{C}_0$ assumes that the stock weighting cannot exceed 10 times the weighting in the benchmark portfolio and that the sector deviation is between 50% and 200%.

The results for the MSCI World Index are shown in Figure 10. We note that the tracking error is moderate for Scopes 1 and 2, but not for Scope 3. When we include the weighting constraints, the impact is high for Scope 3, especially if we consider scope 3 upstream (Figure 11). In this last case, the tracking error volatility reaches 200 bps in 2035 for the PAB decarbonization pathway, while it was around 100 bps without weighting constraints.

Figure 10: Tracking error volatility of decarbonized portfolios (MSCI World, Dec. 2021, $\mathcal{C}_0$ constraint)

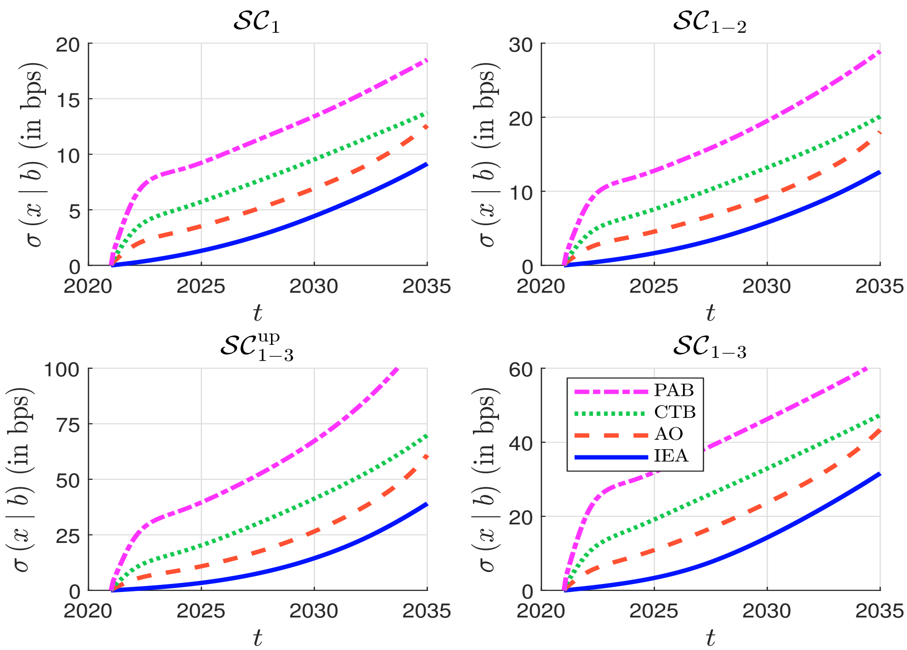


Figure 11: Tracking error volatility of decarbonized portfolios (MSCI World, Dec. 2021, $\mathcal{C}_1$ constraint)

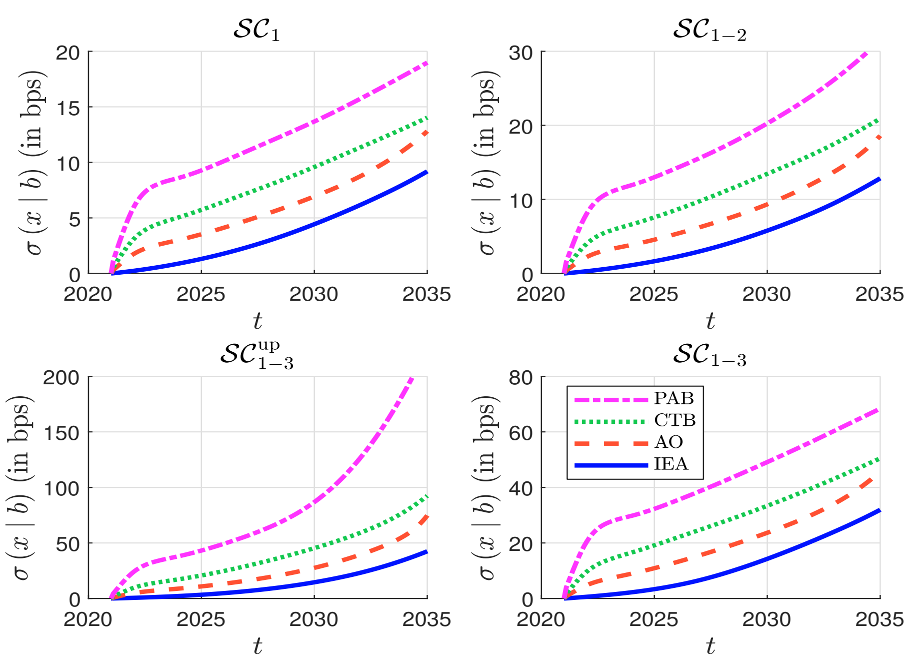


Figure 12: Carbon momentum of decarbonized portfolios (MSCI World, Dec. 2021, $\mathcal{C}_0$ constraint)

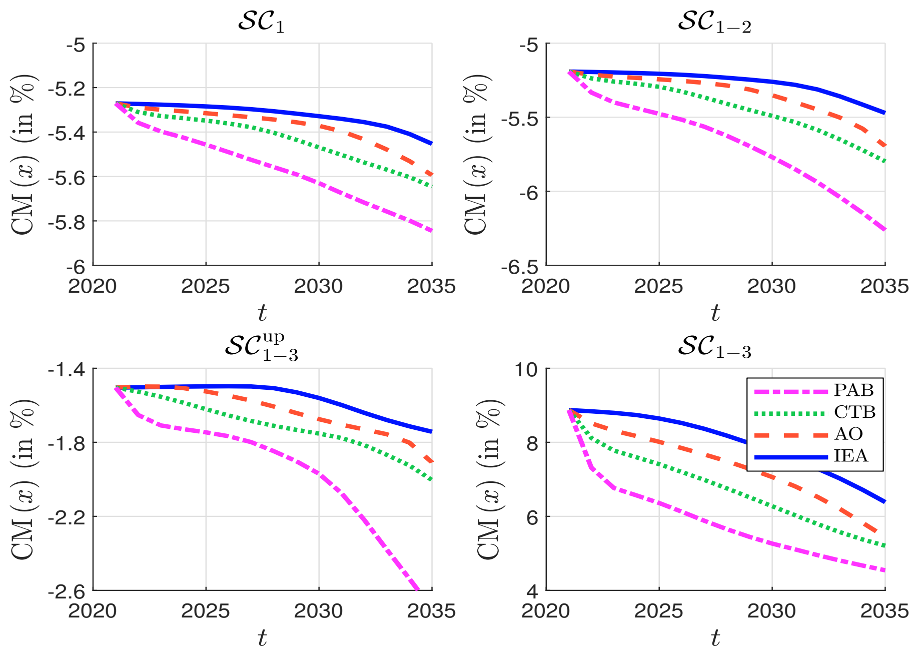
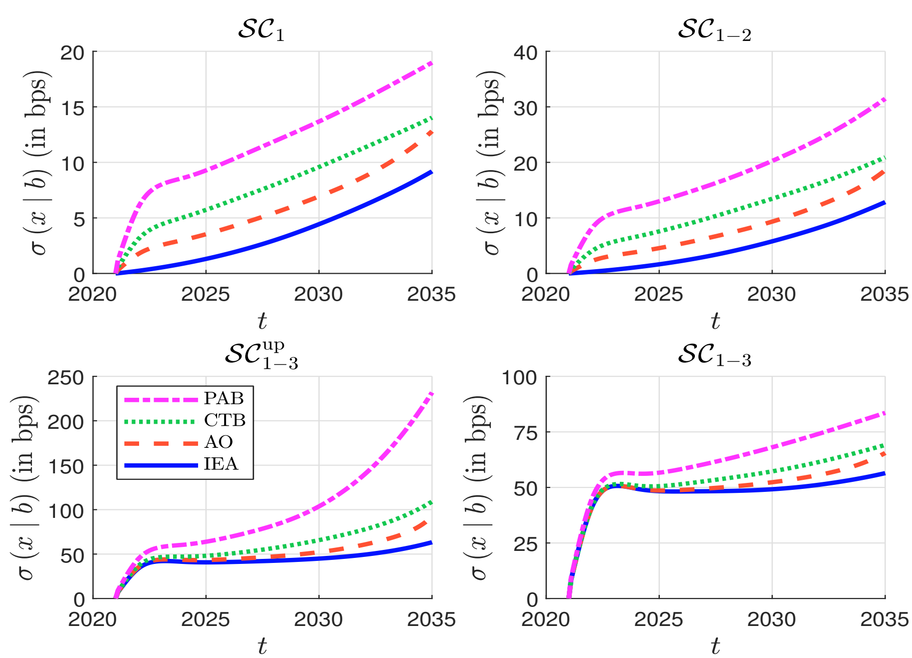


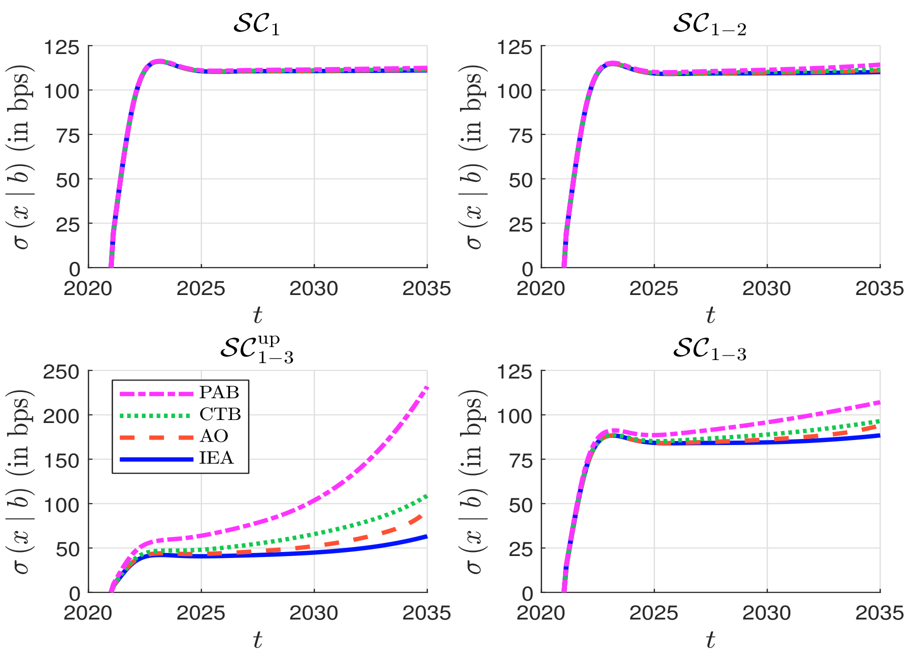
Figure 13: Tracking error volatility of decarbonized portfolios (MSCI World, Dec. 2021, $\mathcal{C}_1$ constraint, $\mathcal{CM}^{\star} = -3.5\%$)



Let us now assess the self-decarbonization of these optimized portfolios. Their carbon momentum $\mathcal{CM}(x)$ are given in Figure 12. We observe that the carbon momentum is negative for Scopes 1, 2 and 3 upstream and it is positive for Scope 3 when we include the downstream emissions. If we implement a self-decarbonization constraint $\mathcal{CM}(x) \leq \mathcal{CM}^{\star}$, the impact will be different depending on the scope and the threshold $\mathcal{CM}^{\star}$. Setting $\mathcal{CM}^{\star}$ to -3.5% gives the results shown in Figure 13.

By adding a bottom-up approach to stock selection, we complete the previous optimization approach. We remove all the stocks that have a high carbon momentum: $\mathcal{CM}_i \geq \mathcal{CM}^{+}$. We can use an absolute threshold (e.g., all the stocks with carbon momentum greater than 10%) or a relative threshold (we remove α% of the stocks). The results are given in Figure 14 when $\mathcal{CM}^{+}$ is equal to 10%. There is a big impact on the tracking error, especially for Scopes 1 and 2. The reason is that some large capitalization companies are excluded because they have a carbon momentum greater than 10%.

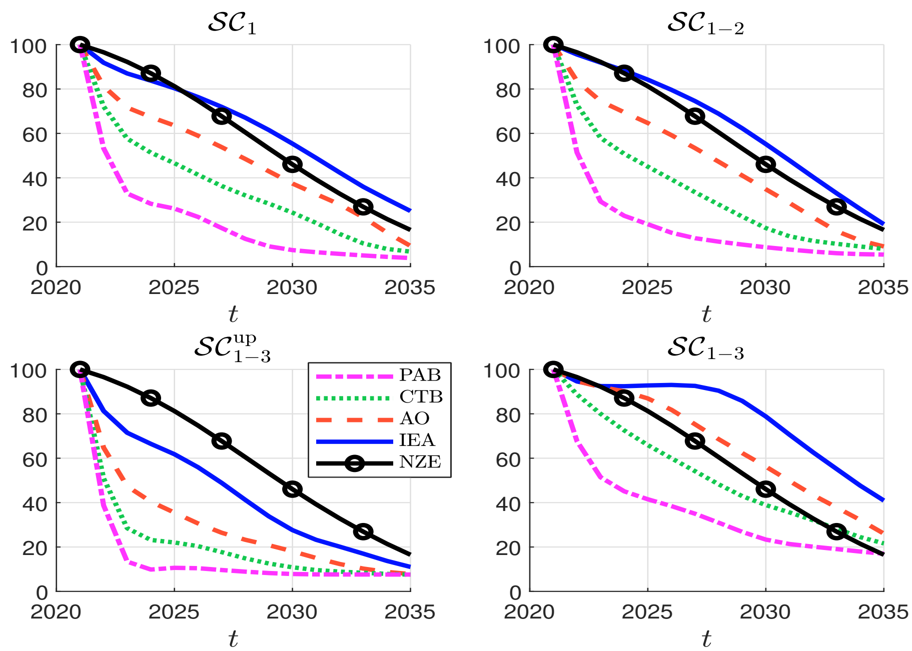
Figure 14: Tracking error volatility of decarbonized portfolios (MSCI World, Dec. 2021, $\mathcal{C}_1$ constraint, $\mathcal{CM}^{\star} = -3.5\%$, $\mathcal{CM}^{+} = 10\%$)



Remark 2. *The empirical results so far show that implementing a decarbonized portfolio is not straightforward. The first challenge is the use of Scope 3 emissions, which introduces an additional and significant tracking risk. This challenge is topical as many investors have begun to implement net-zero by considering Scope 1 and 2 emissions, but with the goal of including Scope 3 emissions in a few years. Most of them will certainly switch to Scope 3 upstream in 2023 and 2024 and experience a jump in their tracking error risk. The second challenge is the management of self-decarbonization, which can be achieved by imposing a global carbon momentum constraint or by considering an exclusion process of the companies making the least effort. Moreover, the previous results cannot be generalized to other investment universes. In fact, we do not obtain homogeneous results between global, American, European or emerging market universes. Nevertheless, we generally find that the issues are more relevant for small equity universes than for large equity universes.*

As noted above, the construction of the core portfolio in the context of net-zero is not just a question of decarbonization path. We have already seen how to account for self-decarbonization by imposing a global carbon momentum constraint and excluding the worst performers. What remains to be seen is whether the core portfolio is consistent with the International Energy Agency's sequencing principle. In particular, the issue of electricity is central to the net-zero scenario. Electricity must be green by 2035. From a financial perspective, this means that we will have to finance the transition of the power sector on a massive scale. In Figure 15, we calculate the decarbonization pathways for the utilities sector and compare them to the sectoral path shown in Figure 3 on page 6. We see that the CTB and PAB portfolios produce a very aggressive path for the power sector. For example, if we include upstream Scope 3 emissions, the carbon intensity of the power sector is close to zero. This means that we have removed all issuers with a high or medium carbon intensity from the portfolio. In other words, we no longer invest in issuers that produce brown electricity or a green-brown electricity mix. We only invest in pure players that produce green electricity, and don't give others time to transform their business models. This does not fit with the goal of net-zero investing. Looking at the AO pathway, it produces a decarbonization path for the utilities sector that is steeper than the NZE scenario. Nevertheless, it is a better solution than the CTB and PAB frameworks.

Figure 15: Decarbonization pathway of the electricity sector (MSCI World, Dec. 2021, $\mathcal{C}_1$ constraint, $\boldsymbol{\mathcal{CM}}^\star = -3.5\%$, $\boldsymbol{\mathcal{CM}}^+ = 10\%$)



The solution is to constrain the optimization problem to follow the NZE scenario for the electricity sector. Following Roncalli (2023), the constraint to meet a reduction rate for a given sector $\mathcal{S}_j$ can be expressed as:

$$\frac{\sum_{i=1}^{n} \mathbb{1}\left\{i \in \mathcal{S}_j\right\} \cdot x_i \cdot \boldsymbol{\mathcal{CI}}_i}{\sum_{i=1}^{n} \mathbb{1}\left\{i \in \mathcal{S}_j\right\} \cdot x_i} = \left(1 - \boldsymbol{\mathcal{R}}_j\right) \frac{\sum_{i=1}^{n} \mathbb{1}\left\{i \in \mathcal{S}_j\right\} \cdot b_i \cdot \boldsymbol{\mathcal{CI}}_i}{\sum_{i=1}^{n} \mathbb{1}\left\{i \in \mathcal{S}_j\right\} \cdot b_i}$$

Let $\boldsymbol{\mathcal{CI}}\left(\mathcal{S}_j, \boldsymbol{\mathcal{R}}_j\right)$ be the absolute value of the carbon intensity target for the given sector.

We have:

$$\mathcal{CI}\left(\mathcal{S}_j,\mathcal{R}_j\right)=\left(1-\mathcal{R}_j\right)\frac{\sum_{i=1}^{n}\mathbb{1}\left\{i\in\mathcal{S}_j\right\}\cdot b_i\cdot\mathcal{CI}_i}{\sum_{i=1}^{n}\mathbb{1}\left\{i\in\mathcal{S}_j\right\}\cdot b_i}$$

We deduce that:

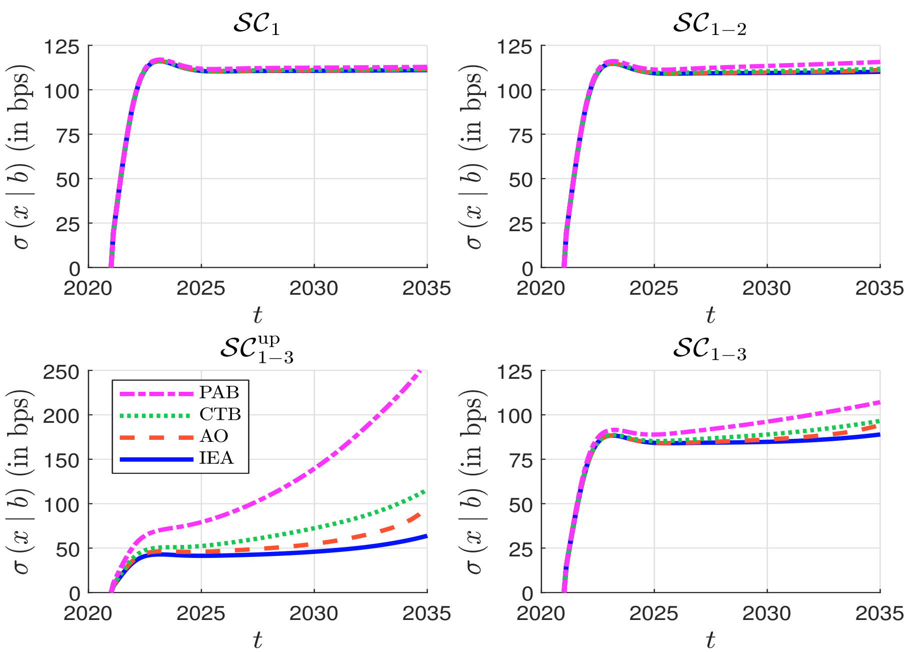
$$\sum_{i=1}^{n}\mathbb{1}\left\{i\in\mathcal{S}_j\right\}\cdot x_i\cdot\mathcal{CI}_i=\mathcal{CI}\left(\mathcal{S}_j,\mathcal{R}_j\right)\sum_{i=1}^{n}\mathbb{1}\left\{i\in\mathcal{S}_j\right\}\cdot x_i$$

which is equivalent to the following constraint:

$$\sum_{i=1}^{n}\mathbb{1}\left\{i\in\mathcal{S}_j\right\}\cdot x_i\cdot\left(\mathcal{CI}_i-\mathcal{CI}\left(\mathcal{S}_j,\mathcal{R}_j\right)\right)=0$$

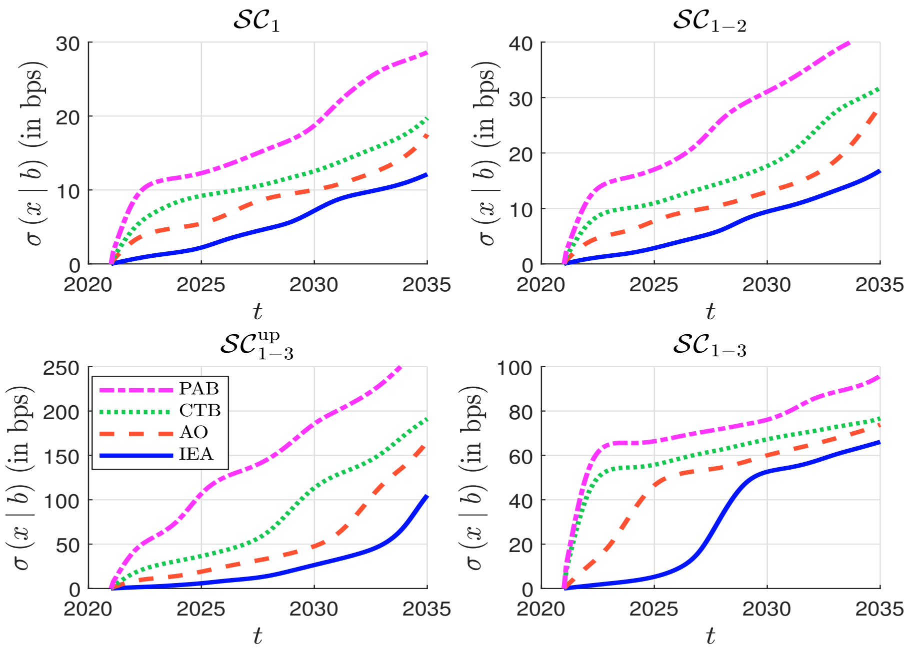
Since this is a linear equation, the optimization problem with this constraint remains a QP problem and can be solved easily. Results are reported in Figure 16. Compared to the results obtained in Figure 15, we observe a small increase in the volatility of the tracking error. The maximum difference is 28 bps (or 12%) in 2035 for the PAB scenario and upstream Scope 3 emissions.

Figure 16: Tracking error volatility of decarbonized portfolios (MSCI World, Dec. 2021, $\mathcal{C}_1$ constraint, $\mathcal{CM}^{\star}=-3.5\%$, $\mathcal{CM}^{+}=10\%$, IEA NZE scenario for the electricity sector)



Remark 3. *The previous analysis gives a lower bound on the tracking error risk because we use the optimization strategy. If we consider the exclusion strategy, the tracking error risk is multiplied by a factor of at least 25%. For example, we get Figure 17 instead of Figure 10 when we consider the $\mathcal{C}_0$ constraint. In this specific case, the tracking error volatility is between 50% and 100% higher. Adding the $\mathcal{C}_1$ constraint helps to reduce the difference in tracking error risk, but it remains important.*

Figure 17: Tracking error volatility of decarbonized portfolios (MSCI World, Dec. 2021, $\mathcal{C}_0$ constraint, exclusion strategy)



Bond portfolios The results for the Global Corporate Index in terms of decarbonisation and self-decarbonisation are shown in Figures 18 and 19. They are consistent with those already seen for equities. We find that the active risk[6] is moderate for Scopes 1 and 2, but not for Scope 3. Indeed, whether we look at Scope 3 with or without downstream, the active risk reaches 30% in 2035 for the PAB decarbonisation pathway, while it is below 12.5% for the first two scopes. We also observe that the carbon momentum is negative for Scopes 1, 2 and 3 upstream and it is positive for Scope 3 when we include the downstream emissions.

In Figure 20, we implement a self-decarbonisation constraint $\mathcal{CM}(x) \leq -3.5\%$. The impact on active risk is zero or negligible for Scopes $1+2$, as the carbon momentum of the decarbonised portfolios is already at or below the -3.5% threshold. However, the constraint adds 10% and 20% of active risk in the early years for Scopes $1-3$ upstream and full Scopes $1-3$. By 2035, the additional active risk in the PAB decarbonisation pathway is 0% and 5%. Assume that the absolute limit $\mathcal{CM}^+$ for the carbon momentum is 10% and that all bonds with a carbon momentum above this limit are removed. The results are shown in Figure 21, and as with equities, the effect of this constraint is strongly reflected across all scopes, with active risk rising above 15% for Scopes 1 and 2 and rising to 50% for full Scopes $1-3$.

As noted above, the electricity sector is a critical part of the transition and must be green by 2035. Figure 22 shows the decarbonisation path of this sector for the 4 pathways considered and compares it with the International Energy Agency's NZE scenario. Looking

[6] Active risk is the sum of active share and DTS deviation:

$$\mathcal{AR}(x \mid b) = \frac{1}{2}\sum_{i \in b}|x_i - b_i| + 50 \sum_{s=1}^{n_{Sector}} \left| \sum_{i \in s}(x_i - b_i) \cdot \mathrm{DTS}_i \right|$$

To make the two risk dimensions comparable, we use a factor of 50 for the DTS active risk.

Figure 18: Active risk of decarbonized portfolios (Global Corporate, Dec. 2021)

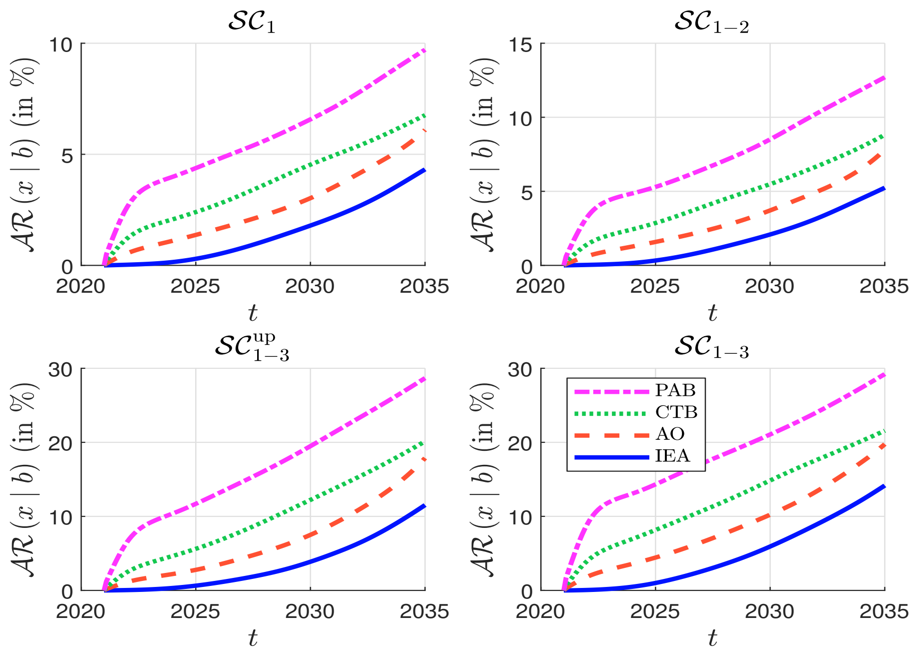


Figure 19: Carbon momentum of decarbonized portfolios (Global Corporate, Dec. 2021)

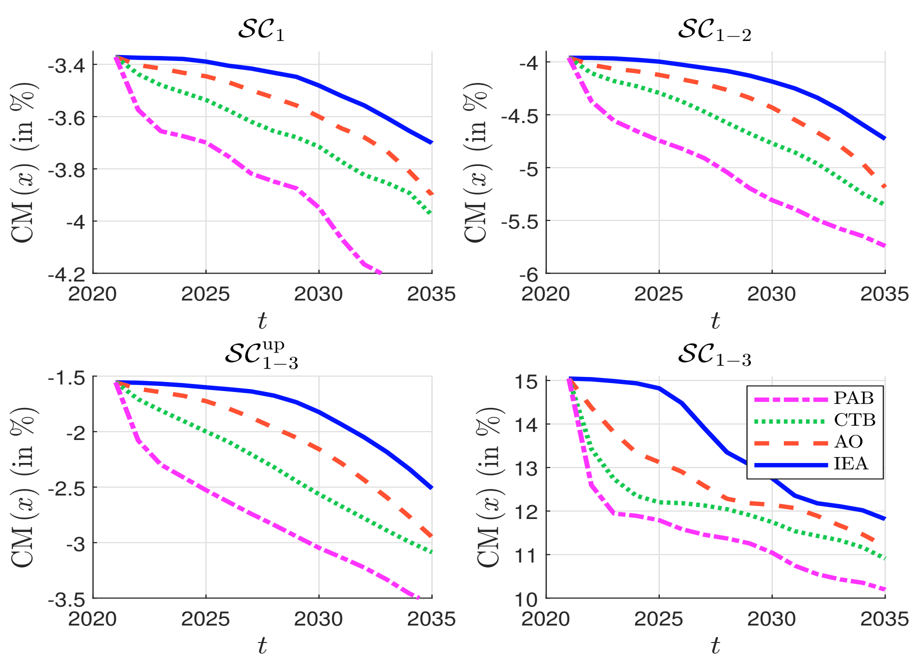


Figure 20: Active risk of decarbonized portfolios (Global Corporate, Dec. 2021, $\mathcal{CM}^{\star} = -3.5\%$)

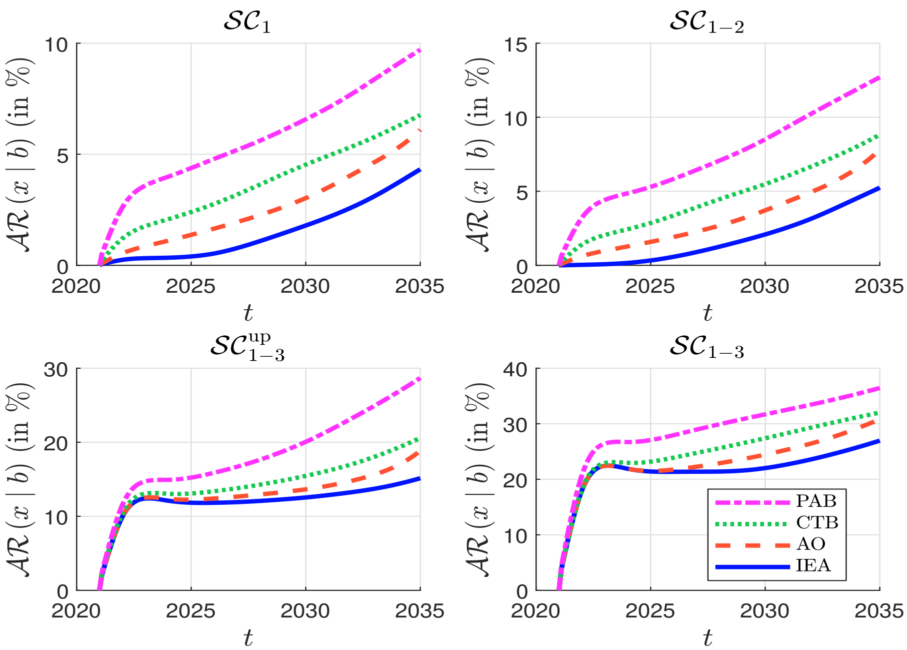
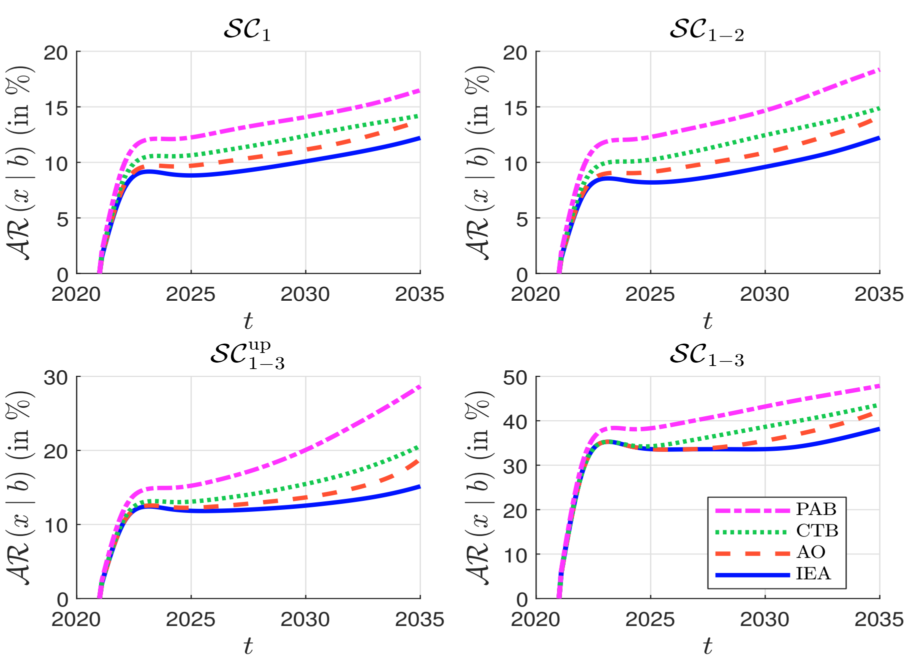
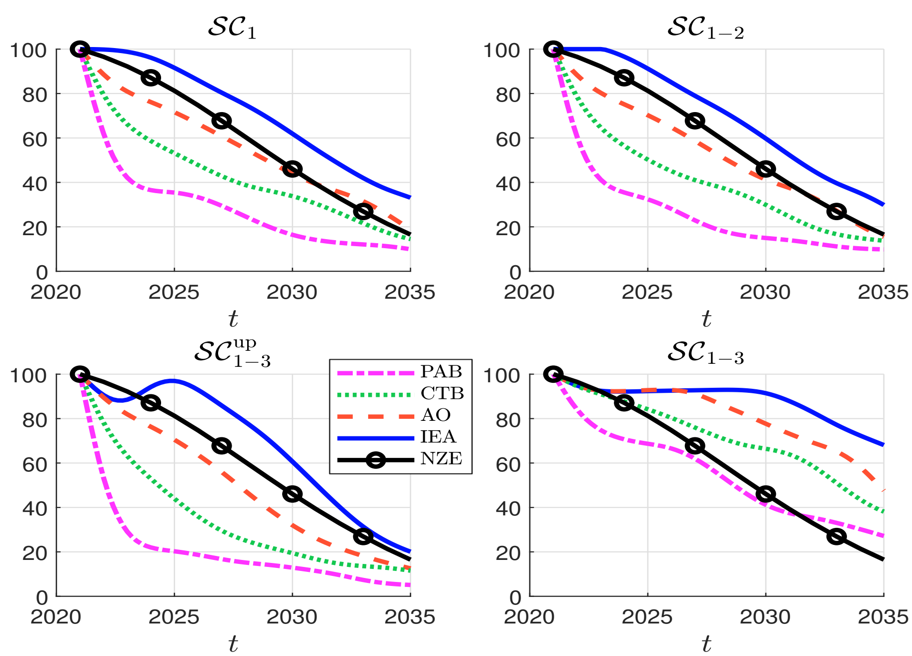


Figure 21: Active risk of decarbonized portfolios (Global Corporate, Dec. 2021, $\mathcal{CM}^{\star} = -3.5\%$, $\mathcal{CM}^{+} = 10\%$)



at Scopes 1, 2 and 3 upstream, the same can be said for the bond portfolio as for the equity portfolio, with the PAB and CTB pathways being far too aggressive compared to the needs of the NZE scenario, while the AO pathway is the closest. However, if we include the full Scope 3, the PAB pathway is closer to the NZE pathway. The other pathways are much slower and will not decarbonise the sector in time. In Figure 23, we have constrained the utilities sector to follow the NZE scenario. Compared to Figure 21, the active risk is higher for all the paths. This is particularly the case for the PAB and CTB pathways, which experience quite an increase when considering Scopes 1 + 2 and the Scope 3 upstream.

Figure 22: Decarbonization pathway of the electricity sector (Global Corporate, Dec. 2021, $\mathcal{CM}^{\star} = -3.5\%$, $\mathcal{CM}^{+} = 10\%$)



As with the equity portfolio, we can apply an exclusion strategy, which consists of excluding issuers with high carbon intensity and reallocating the exclusion proceeds by minimising the active risk. Compared to the equity portfolio, the impact of the exclusion strategy on the active risk is rather negligible (Figure 24), as it is close to the active risk shown in Figure 18.

Remark 4. *The previous results are global and do not distinguish between active share risk and DTS matching risk. If we focus on the latter, we see that it takes a very low value, implying that active risk is mainly explained by active share. This confirms the results of Barahhou et al. (2022), who found that it is easier to implement net-zero strategies in corporate bonds than in equity bonds. In fact, we find that the bond market is going green faster than the equity market, certainly because of new bond issuance and the role of the primary market.*

Figure 23: Active risk of decarbonized portfolios (Global Corporate, Dec. 2021, $\mathcal{CM}^\star = -3.5\%$, $\mathcal{CM}^+ = 10\%$, IEA NZE scenario for the electricity sector)

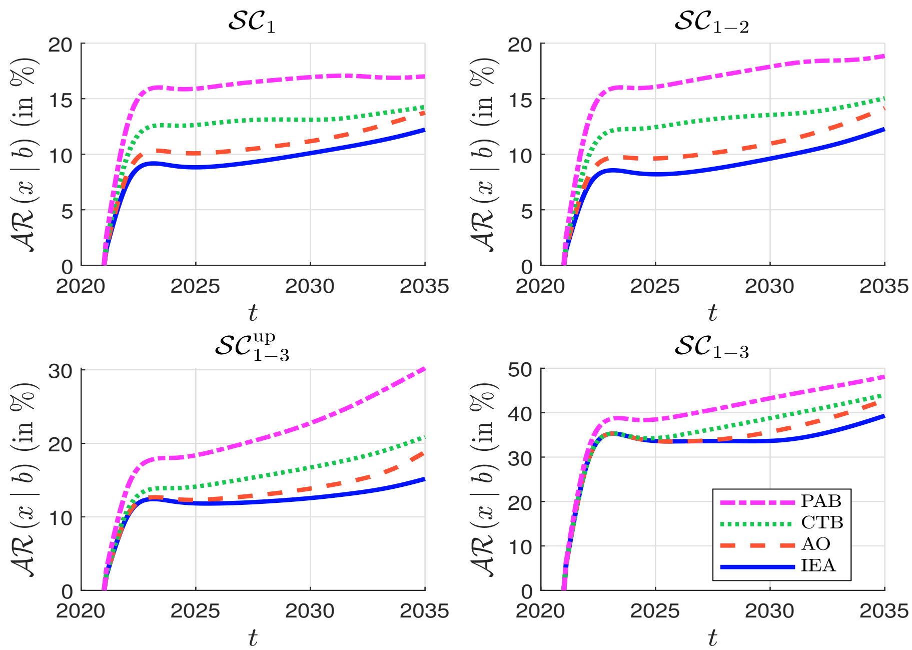
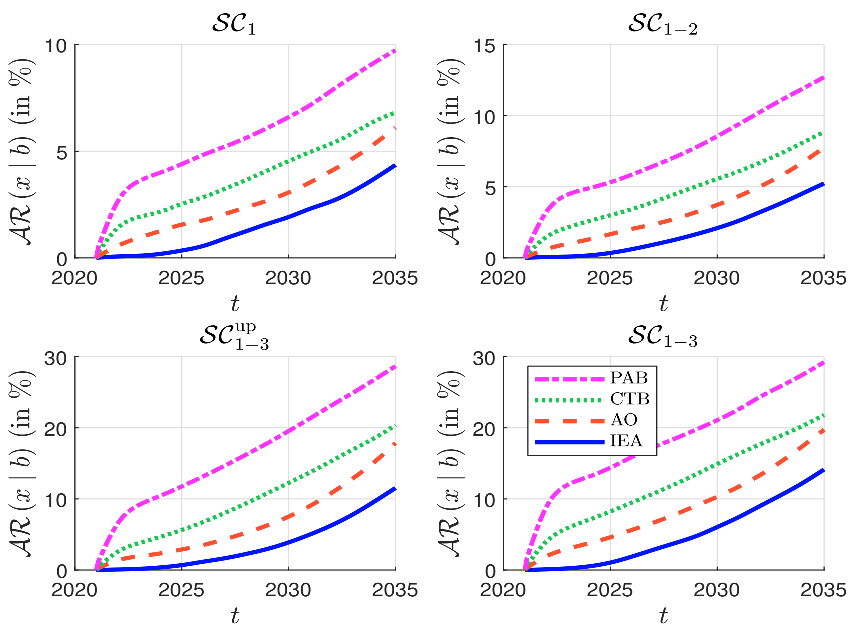


Figure 24: Active risk of decarbonized portfolios (Global Corporate, Dec. 2021, exclusion strategy)



2.2 Implications for strategic asset allocation

Using the Black-Litterman model, we can define the implied risk premia given a portfolio x. Following Roncalli (2013), we have:

$$\tilde{\pi}_i := \tilde{\mu}_i - r = \mathrm{SR}\left(x \mid r\right) \cdot \frac{(\Sigma x)_i}{\sqrt{x^\top \Sigma x}}$$

where $\tilde{\pi}_i$ is the implied risk premium of Asset i, $\tilde{\mu}_i$ is the implied expected return, r is the risk-free rate, $\mathrm{SR}\left(x \mid r\right)$ is the Sharpe ratio of the portfolio and Σ is the covariance matrix. We calculate the implied risk premium of a given sector $\mathcal{S}_j$ as follows:

$$\tilde{\pi}_j = \frac{\sum_{i \in \mathcal{S}_j} x_i \tilde{\pi}_i}{\sum_{i \in \mathcal{S}_j} x_i}$$

In what follows, we assume that $\mathrm{SR}\left(x \mid r\right) = 0.35$.

Table 7: Factors influencing risk premia (MSCI World, Dec. 2021, $\mathcal{C}_0$ constraint)

Year		2035	2050	2035	2035
Pathway	b	PAB	PAB	PAB	IEA
Scope		$\mathcal{SC}_1$	$\mathcal{SC}_1$	$\mathcal{SC}_{1-3}$	$\mathcal{SC}_1$
Communication Services	4.01%	3.96%	3.88%	3.86%	3.99%
Consumer Discretionary	4.45%	4.42%	4.43%	4.53%	4.43%
Consumer Staples	2.58%	2.58%	2.62%	2.73%	2.57%
Energy	5.43%	5.57%	6.87%	7.04%	5.53%
Financials	4.68%	4.65%	4.59%	4.67%	4.66%
Health Care	3.22%	3.23%	3.26%	3.28%	3.22%
Industrials	3.94%	3.96%	4.03%	3.66%	3.95%
Information Technology	5.21%	5.17%	5.12%	5.02%	5.19%
Materials	3.97%	3.92%	3.55%	4.10%	3.97%
Real Estate	3.71%	3.68%	3.64%	3.82%	3.68%
Utilities	3.31%	3.09%	2.59%	2.64%	3.15%
Portfolio	4.24%	4.24%	4.24%	4.24%	4.24%

In Table 7, we report the factors influencing risk premia. The first columns shows the risk premia when considering the benchmark. Energy is the sector with the highest risk premium, while Consumer Staples is the sector with the lowest risk premium (5.43% vs. 2.58%). The risk premium of the benchmark is equal to 4.24%. If we now consider the net-zero portfolio calibrated in 2035 with the PAB decarbonization pathway and Scope 1 emissions, the results change slightly. The largest deviation is observed for the Utilities sector with a lower risk premium of 22 bps. In addition to portfolio construction, three factors affect the implied risk premium. The first factor is the time horizon. The difference between the second and third columns is the year of decarbonization (2035 vs. 2050). The risk premium of the portfolio does not change and remains at 4.24%. However, the Energy sector experiences a large increase of its risk premium (6.87% vs. 5.57%) while the risk premia of some sectors suffer greatly, such as Materials (-37 bps) and Utilities (-50 bps). The second factor is the scope of carbon emissions. For example, including Scope 3 emissions has a greater impact on the risk premium. In the case of the Industrials sector, the risk premium is 3.66% for Scope 3 emissions and 3.96% for Scope 1 emissions. The last factor is the choice of the decarbonization pathway. The choice of the IEA scenario has a moderate impact compared to the PAB scenario.

Table 8: Implied risk premia in % (MSCI World, Dec. 2021, AO decarbonization pathway, 2035)

Optimization		Problem $\mathcal{P}_1$						Problem $\mathcal{P}_2$						Problem $\mathcal{P}_3$	
Scope	b	$\mathcal{SC}_{1-2}$		$\mathcal{SC}_{1-3}^{\text{up}}$		$\mathcal{SC}_{1-3}$		$\mathcal{SC}_{1-2}$		$\mathcal{SC}_{1-3}^{\text{up}}$		$\mathcal{SC}_{1-3}$		$\mathcal{SC}_{1-2}$	
Statistics		$\tilde{\pi}_j$	$\Delta\tilde{\pi}_j$	$\tilde{\pi}_j$	$\Delta\tilde{\pi}_j$	$\tilde{\pi}_j$	$\Delta\tilde{\pi}_j$	$\tilde{\pi}_j$	$\Delta\tilde{\pi}_j$	$\tilde{\pi}_j$	$\Delta\tilde{\pi}_j$	$\tilde{\pi}_j$	$\Delta\tilde{\pi}_j$	$\tilde{\pi}_j$	$\Delta\tilde{\pi}_j$
Communication Services	4.01	3.97	−0.05	3.76	−0.25	3.90	−0.11	4.03	0.02	3.88	−0.14	3.91	−0.10	4.03	0.01
Consumer Discretionary	4.45	4.41	−0.03	4.56	0.12	4.50	0.05	4.46	0.02	4.60	0.15	4.72	0.27	4.47	0.02
Consumer Staples	2.58	2.59	0.01	2.64	0.06	2.70	0.12	2.64	0.05	2.41	−0.17	2.72	0.13	2.64	0.05
Energy	5.43	5.59	0.17	6.60	1.17	5.32	−0.11	5.56	0.13	6.23	0.81	5.05	−0.37	5.55	0.12
Financials	4.68	4.62	−0.06	4.31	−0.36	4.67	−0.00	4.71	0.03	4.40	−0.27	4.61	−0.07	4.70	0.02
Health Care	3.22	3.22	−0.00	3.22	−0.00	3.27	0.05	3.26	0.04	3.37	0.15	3.36	0.14	3.26	0.04
Industrials	3.94	3.96	0.02	3.86	−0.08	3.83	−0.11	4.09	0.15	3.65	−0.29	3.86	−0.08	4.08	0.14
Information Technology	5.21	5.17	−0.04	5.02	−0.18	5.08	−0.12	5.03	−0.17	4.93	−0.28	5.02	−0.18	5.03	−0.18
Materials	3.97	3.93	−0.05	2.61	−1.36	4.04	0.07	4.08	0.10	3.53	−0.45	4.37	0.40	4.02	0.05
Real Estate	3.71	3.79	0.09	3.71	0.00	3.76	0.05	3.95	0.25	3.57	−0.13	3.71	0.01	3.96	0.26
Utilities	3.31	2.93	−0.38	1.31	−2.00	3.13	−0.18	2.68	−0.63	2.51	−0.80	2.99	−0.32	2.98	−0.33
Portfolio	4.24	4.24	0.00	4.25	0.00	4.24	−0.00	4.23	−0.02	4.25	0.00	4.23	−0.01	4.23	−0.02

Table 9: Implied risk premia in % (MSCI World, Dec. 2021, PAB decarbonization pathway, 2035)

Optimization		Problem $\mathcal{P}_1$						Problem $\mathcal{P}_2$						Problem $\mathcal{P}_3$	
Scope	b	$\mathcal{SC}_{1-2}$		$\mathcal{SC}_{1-3}^{\text{up}}$		$\mathcal{SC}_{1-3}$		$\mathcal{SC}_{1-2}$		$\mathcal{SC}_{1-3}^{\text{up}}$		$\mathcal{SC}_{1-3}$		$\mathcal{SC}_{1-2}$	
Statistics		$\tilde{\pi}_j$	$\Delta\tilde{\pi}_j$	$\tilde{\pi}_j$	$\Delta\tilde{\pi}_j$	$\tilde{\pi}_j$	$\Delta\tilde{\pi}_j$	$\tilde{\pi}_j$	$\Delta\tilde{\pi}_j$	$\tilde{\pi}_j$	$\Delta\tilde{\pi}_j$	$\tilde{\pi}_j$	$\Delta\tilde{\pi}_j$	$\tilde{\pi}_j$	$\Delta\tilde{\pi}_j$
Communication Services	4.01	3.96	−0.05	4.00	−0.01	3.86	−0.16	4.05	0.03	3.83	−0.18	3.87	−0.14	4.05	0.04
Consumer Discretionary	4.45	4.43	−0.02	4.89	0.44	4.53	0.08	4.49	0.04	4.26	−0.19	4.83	0.38	4.49	0.04
Consumer Staples	2.58	2.63	0.05	2.69	0.11	2.73	0.15	2.68	0.10	2.61	0.02	2.71	0.13	2.69	0.10
Energy	5.43	5.46	0.03	6.60	1.17	7.04	1.61	5.37	−0.06	6.43	1.00	4.80	−0.63	5.24	−0.19
Financials	4.68	4.57	−0.11	4.10	−0.58	4.67	−0.00	4.65	−0.03	3.96	−0.71	4.58	−0.10	4.61	−0.07
Health Care	3.22	3.23	0.01	4.10	0.88	3.28	0.06	3.28	0.06	4.82	1.60	3.36	0.14	3.27	0.05
Industrials	3.94	3.96	0.02	3.34	−0.61	3.66	−0.28	4.08	0.14	3.39	−0.55	3.79	−0.15	4.06	0.11
Information Technology	5.21	5.14	−0.07	4.89	−0.32	5.02	−0.19	5.00	−0.20	4.82	−0.39	4.98	−0.23	4.98	−0.22
Materials	3.97	3.74	−0.24	1.03	−2.95	4.10	0.13	3.61	−0.37	3.96	−0.02	4.26	0.28	3.51	−0.47
Real Estate	3.71	3.88	0.18	3.78	0.08	3.82	0.12	3.98	0.27	4.11	0.40	3.83	0.13	3.91	0.20
Utilities	3.31	2.03	−1.28	0.97	−2.34	2.64	−0.67	2.41	−0.90	2.49	−0.82	2.76	−0.55	2.97	−0.34
Portfolio	4.24	4.24	0.00	4.25	0.01	4.24	−0.01	4.23	−0.02	4.28	0.03	4.23	−0.02	4.23	−0.02

Figure 25: Implied risk premium $\Delta\tilde{\pi}_j$ in bps of the Utilities sector (MSCI World, Dec. 2021, Scope $\boldsymbol{\mathcal{SC}}_{1-2}$)

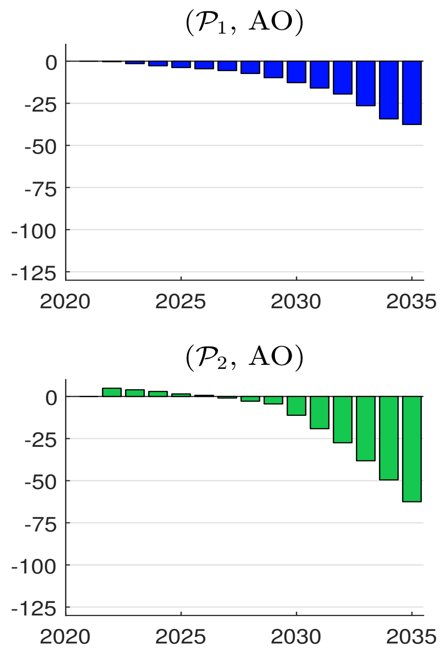
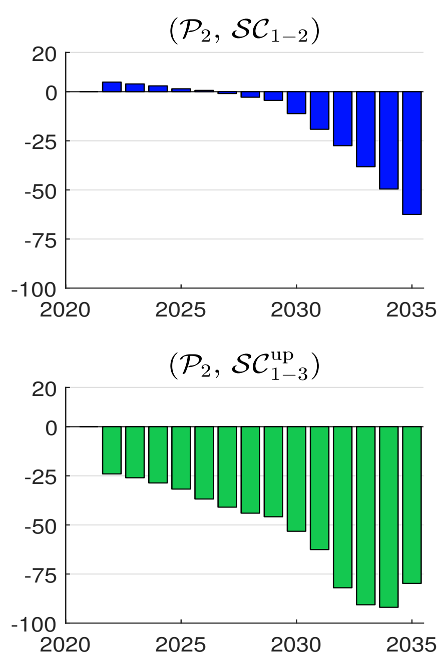


Figure 26: Implied risk premium $\Delta\tilde{\pi}_j$ in bps of the Utilities sector (MSCI World, Dec. 2021, AO pathway)



In Tables 8 and 9, we show the implied risk premium $\tilde{\pi}_j$ of the sector $\mathcal{S}_j$ and the difference $\Delta\tilde{\pi}_j = \tilde{\pi}_j(x) - \tilde{\pi}_j(x)$ with respect to the benchmark. We consider three previous optimization problems:

- Problem $\mathcal{P}_1$: optimization with $\mathcal{C}_0$ constraint;
- Problem $\mathcal{P}_2$: optimization with $\mathcal{C}_1$ constraint, $\boldsymbol{\mathcal{CM}}^\star = -3.5\%$, $\boldsymbol{\mathcal{CM}}^+ = 10\%$;
- Problem $\mathcal{P}_3$: optimization with $\mathcal{C}_1$ constraint, $\boldsymbol{\mathcal{CM}}^\star = -3.5\%$, $\boldsymbol{\mathcal{CM}}^+ = 10\%$ + IEA NZE scenario for the electricity sector

In Table 8, when we consider the $\mathcal{C}_0$ constraint and Scope $\boldsymbol{\mathcal{SC}}_{1-2}$ emissions, the risk premium of the portfolio relative to the benchmark does not change and is equal to 4.24%, but there are still some differences to take into account, such as the decrease of 38 bps in the risk premium for the Utilities sector. It's really when we consider $\mathcal{SC}_{1-3}^{up}$ emissions that we see an increase in the disparity for several sectors, Utilities, Materials and Energy being the most affected with variations over 100 bps. Taking into account the $\mathcal{C}_1$ and momentum constraints (Problem $\mathcal{P}_2$), we see a slight decrease of 2 bps in the portfolio risk premium for $\mathcal{SC}_{1-2}$. The risk premium for the Utilities sector is significantly lower (2.68% vs. 3.31%). Furthermore, in contrast to the $\mathcal{C}_0$ constraint, there is a smaller impact on the risk premium for the Utilities, Materials and Energy sectors (-80, -45 and $+81$ bps vs. -200, -136 and $+117$ bps), when considering $\mathcal{SC}_{1-3}^{up}$ emissions. Constraining the optimization problem to follow the NZE scenario for the Utilities sector shows a 33 bps reduction in the risk premium for this sector relative to the benchmark (3.31% vs. 2.98%), lower than the 63 bps reduction observed for the $\mathcal{C}_1$ constraint alone. Table 9 helps us look at the impact of the choice of decarbonization pathway, between the PAB and AO pathways. For the $\mathcal{C}_0$ constraint and $\mathcal{SC}_{1-2}$ emissions, the Utilities sector experiences a larger decrease in its risk premium when looking at the PAB pathway than the AO pathway (-128 bps vs. -38 bps), the same can be said for the Materials sector. If we now look at the $\mathcal{SC}_{1-3}^{up}$ emissions, the effect of pathway choice on risk premium becomes even more pronounced. The Materials, Healthcare, and Industrials sectors are the most affected. The Materials sector experiences a significant 295 bps decrease in its risk premium with the PAB pathway, compared to a 136 bps decrease with the AO pathway. The Healthcare sector sees its risk premium remain unchanged under the AO pathway, while it increases by 88 bps under the PAB pathway. These differences can also be seen for the $\mathcal{C}_1$ constraint, with the Health Care sector remaining the most affected with a variation of 160 bps for the PAB pathway versus 15 bps for the AO pathway.

Figures 25 and 26 focus on the Utilities sector, which is the most important sector for achieving net-zero. These results allow us to understand which factor most influences the implied risk premium of the Utilities sector, the scope of carbon emissions, the decarbonization pathway or the optimization constraints. In Figure 25, we have fixed the level of carbon emissions factor (Scope $\mathcal{SC}_{1-2}$ emissions) and applied the two optimization problems $\mathcal{P}_1$ and $\mathcal{P}_2$. In both problems, the discrepancy in the implied risk premium relative to the benchmark is much more important when the PAB pathway is considered. In Figure 26, we look at the evolution of the implied risk premium through the AO pathway, alternating between scopes and constraints. Looking at the second optimization problem, the risk premium reacts strongly to the addition of $\mathcal{SC}_3^{up}$ emissions with a downward variation that reaches 80 bps in 2035. If we now compare the third optimization problem with the second for $\mathcal{SC}_{1-2}$, the story is quite different. For $\mathcal{P}_2$, we see a small upward variation until 2026, when it decreases to reach a variation of 63 bps. But for the third optimisation problem, the upward variation of the risk premium is more important, reaching 20 bps, and longer, until 2030, when it decreases to reach a variation of 33 bps.

Let $x(t_0)$ and $\pi(t_0)$ be the vector of baseline portfolio weights and risk premia. We note $x(t)$ and $\pi(t)$ the corresponding values for the optimization solution. We have the following performance attribution:

$$x(t)^\top \pi(t) - x(t_0)^\top \pi(t_0) = \underbrace{\left(x(t) - b\right)^\top \pi(t_0)}_{\text{Allocation}} + \underbrace{b^\top \left(\pi(t) - \pi(t_0)\right)}_{\text{Selection}} + \underbrace{\left(x(t) - b\right)^\top \left(\pi(t) - \pi(t_0)\right)}_{\text{Interaction}}$$

Three effects come into play. The allocation (A) effect measures the impact of the sector allocation. The selection (S) effect is the value added by the picking process within each sector. Finally, the interaction (I) effect captures the interaction between the allocation and selection effects. The three attribution terms sum exactly to the active return (AR).

Table 10 shows the performance attribution of two net-zero portfolios in 2035, considering the AO pathway with the third optimization problem. As shown in Table 8, the implied risk premium of the net-zero portfolio relative to the benchmark, including $\mathcal{SC}_{1-2}$ emissions, falls by 2 bps to 4.23%. This is mainly due to a strong absolute active return for the Information Technology sector (-18.4 bps) and the Financials sector (19 bps). The Information Technology sector is the most affected by the three effects, with an allocation effect of -14.7 bps, a selection effect of -4.2 bps and an interaction effect of 0.5 bps. As for the Financials sector, its high active return is mainly due to a significant allocation effect of 18.9 bps. Taking into account $\mathcal{SC}_{1-3}^{up}$, the portfolio is characterized by a rather low active return of 0.2 bps, made up of a strong positive allocation effect of 18.4 bps and a strong negative selection and interaction effect of -13.8 bps and -4.3 bps respectively. The sectors contributing most to this allocation effect are Financials (61.5 bps), Information Technology (17.6 bps), Consumer Discretionary (-15.6 bps), Industrials (-15.2 bps) and Health Care (-15 bps). The same sectors, with the exception of Consumer Discretionary, lead the negative selection effect. The interaction effect is driven by the Financials, Industrials and Energy sectors (-3.8 bps, -1.3 bps and 1.3 bps, respectively).

Table 10: Performance attribution (in bps) of net-zero core portfolios (MSCI World, Dec. 2021, Problem $\mathcal{P}_3$)

Scope	$\mathcal{SC}_{1-2}$				$\mathcal{SC}_{1-3}^{\text{up}}$			
Effect	(A)	(S)	(I)	(AR)	(A)	(S)	(I)	(AR)
Communication Services	2.0	0.1	0.0	2.2	7.4	-1.2	-0.3	5.9
Consumer Discretionary	3.9	0.2	0.0	4.1	-15.6	2.2	-0.6	-14.1
Consumer Staples	-0.0	0.4	-0.0	0.4	-8.9	-1.2	0.6	-9.5
Energy	-6.8	0.4	-0.1	-6.6	-8.5	2.6	-1.3	-7.2
Financials	18.6	0.3	0.1	19.0	61.5	-3.8	-3.8	54.0
Health Care	3.7	0.5	0.0	4.3	-15.0	2.9	-1.1	-13.2
Industrials	4.6	1.4	0.2	6.2	-15.2	-3.5	1.3	-17.4
Information Technology	-14.7	-4.2	0.5	-18.4	17.6	-7.4	-1.1	9.1
Materials	-8.3	0.2	-0.1	-8.2	-8.3	-1.9	1.0	-9.2
Real Estate	-0.5	0.7	-0.0	0.2	7.9	-0.3	-0.2	7.3
Utilities	-4.5	-0.9	0.5	-5.0	-4.5	-2.3	1.1	-5.7
Portfolio	-2.0	-0.8	1.0	-1.8	18.4	-13.8	-4.3	0.2

The same exercise is performed in Table 11, this time for the net-zero sectors. Looking at $\mathcal{SC}_{1-2}$, we see that the Utilities sector has the largest active return in absolute terms (-33.4 bps), followed by Real Estate (25.6 bps) and Information Technology (-17.6 bps). The active return of the Utilities sector is driven by its significant allocation effect (-34.5 bps), the same can be said for the Real Estate sector (24.1 bps), while the Information Technology sector is driven by all three effects (−19.8 bps, −12.1 bps and 14.3 bps). Looking at the $\mathcal{SC}^{up}_{1-3}$, the Energy sector has the largest active return (84.2 bps), closely followed by the Utilities sector (−82.5 bps), then the Materials and Industrials sectors (−45.6 bps and −33.9 bps). The active return of the Energy sector is strongly influenced by its allocation effect (77.6 bps), but also by selection (−2.8 bps) and interaction (9.5 bps), the largest of all sectors. The active return of the Utilities sector is mainly driven by its significant allocation effect (−83.5 bps), while the Materials and Industrials sectors are affected by both the allocation and interaction effects (−52.1 bps and 7 bps vs. 36.8 bps and 3.9 bps, respectively).

Table 11: Performance attribution (in bps) of net-zero sectors (MSCI World, Dec. 2021, Problem $\mathcal{P}_3$)

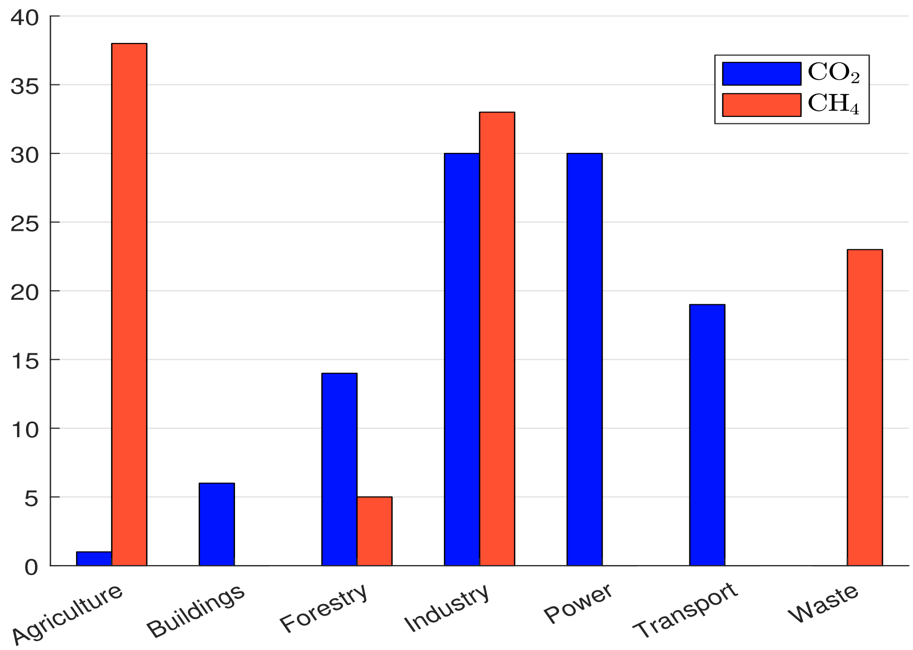
Scope	$\mathcal{SC}_{1-2}$				$\mathcal{SC}^{\text{up}}_{1-3}$			
Effect	(A)	(S)	(I)	(AR)	(A)	(S)	(I)	(AR)
Communication Services	−0.3	1.5	0.2	1.5	−15.2	−0.4	1.0	−14.5
Consumer Discretionary	−0.3	1.8	0.1	1.6	19.0	−2.7	1.4	17.7
Consumer Staples	4.5	0.9	0.2	5.5	−18.9	−1.7	3.6	−17.0
Energy	10.6	0.8	0.3	11.7	77.6	−2.8	9.5	84.2
Financials	0.3	2.0	0.1	2.4	−30.4	1.2	0.7	−28.5
Health Care	2.8	1.4	0.1	4.2	21.9	−1.0	2.1	23.0
Industrials	12.4	1.5	0.2	14.1	−36.8	−1.0	3.9	−33.9
Information Technology	−19.8	−12.1	14.3	−17.6	−31.6	−2.7	3.0	−31.3
Materials	3.7	0.7	0.6	5.0	−52.1	−0.8	7.0	−45.9
Real Estate	24.1	1.2	0.4	25.6	−14.2	0.5	3.2	−10.5
Utilities	−34.5	0.4	0.7	−33.4	−83.5	−0.9	1.9	−82.5

These different results imply that implementing a net-zero investment policy is equivalent to taking some active risk. Sometimes the portfolio manager is unaware of these implicit bets. This is especially true when we independently define a strategic asset allocation and exclusion policy. In addition, we find that the implicit bets change when the net-zero policy is changed. Therefore, we need to understand that a net-zero policy does not have a neutral effect on portfolio behavior, even if we have the impression that tracking error risk is limited. That is, the tracking error is not of the same whether it is a replication strategy or a climate strategy.

3 The satellite portfolio

While the goal of the core portfolio is to implement decarbonization policies, the goal of the satellite portfolio is to finance the transition to a low-carbon economy. In the first case, we need to manage carbon intensity; in the second, we need to monitor green intensity. As shown by Barahhou *et al.* (2022), these two KPI metrics (carbon intensity and green intensity) are now positively correlated. Therefore, reducing carbon footprint and increasing greenness may be contradictory. Separating the core portfolio from the satellite portfolio is motivated by this current issue. However, we can imagine that this contradiction will become less relevant as the economy decarbonizes and moves more towards a net-zero trajectory.

Figure 27: Distribution (in %) of GHG emissions by energy system



Source: McKinsey (2022, Exhibit E3, page 10).

3.1 How to achieve net-zero emissions

When we talk about what's needed to get to net-zero, it's easy to make an endless list. This doesn't help much because we no longer know how to distinguish priority actions from less important things. We can have the same feeling when we listen to portfolio managers talking about net-zero. All too often, it's a pile of constraints and targets that are more ESG criteria than a true net-zero objective. Achieving net-zero would mean a fundamental transformation of the seven energy and land-use systems: agriculture, buildings, forestry and land use, industry, power (electricity and heat generation), transport, and waste (McKinsey, 2022). In Figure 27, we show the source of emissions by energy system. We check that the emissions are concentrated in a small number of systems. Furthermore, an analysis of the roadmaps[7] for achieving the net-zero emissions scenario shows that the main transformation involves the power sector in two directions:

1. Massive electrification of the world economy

2. Greening electricity to achieve clean power generation

The goal of the first factor is to achieve a fully electrified economy, which means that GHG emissions from most of today's polluting activities will be entirely dependent on GHG emissions from the power sector. Examples include road transportation, shipping, buildings and manufacturing processes. The consequence of the first factor is that much of the GHG emissions emitted in the world would depend on the carbon intensity of electricity. The goal of the second factor is then to dramatically reduce the carbon footprint of the power sector by changing the way electricity is generated. The idea is that by 2050, 0% of the world's electricity will be based on fossil fuels. Indeed, if the carbon intensity of electricity

[7] See IEA (2021, 2023) and Energy Transitions Commission (2021, 2023a).

Figure 28: Transforming the global value chain into a net-zero economy

Source: McKinsey (2023, Exhibit 6B, page 12).

is zero, this means that no greenhouse gas emissions are emitted by all the human activities that depend on the electricity sector. In other words, the goal is to change the global value chain (Figure 28). The main implication is that not all sectors are created equal in net-zero investing, and it would not be productive to focus on some sectors whose impact on the net-zero transition is marginal or whose contribution is small.

Table 12: Importance of GICS sectors in net-zero investing

Communication Services	
Consumer Discretionary	
Consumer Staples	
Energy	
Financials	
Health Care	
Industrials	
Information Technology	
Materials	
Real Estate	
Utilities	

In Table 12, we propose a ranking of the GICS sector in terms of the importance of net-zero contribution, and we obtain the following five clusters from the most important to the least important:

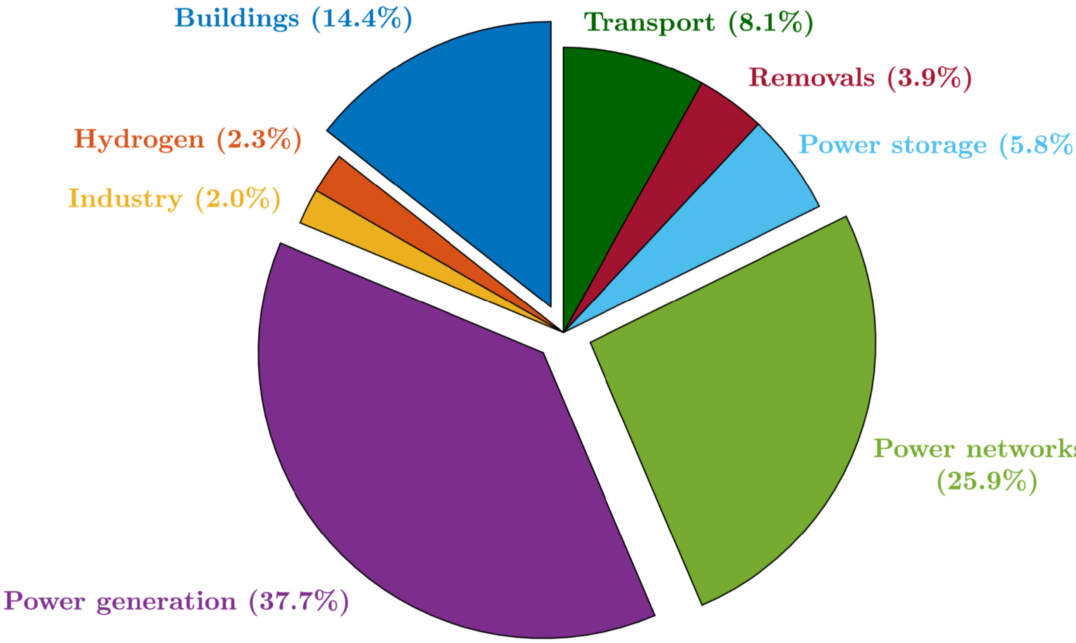
1. Utilities;
2. Materials, Industrials;
3. Consumer Discretionary, Real Estate;
4. Energy, Information Technology, Consumer Staples, Health Care;
5. Financials, Consumer Services.

Below, we discuss some of the key issues related to this ranking and, more generally, the major challenges facing the satellite portfolio.

3.1.1 Funding requirements

According to McKinsey (2022), the world will need about \$275 trillion of investment in physical assets between 2021 and 2050, or \$9.2 trillion per year, to finance the transition to a low-carbon economy. This represents an increase of about \$3.5 trillion per year over today's allocation. More than 85% of this \$275 trillion will go to the buildings, power, transportation sectors (McKinsey, 2023). By region, the most important sectors are transportation in developed markets and energy in emerging markets, including China and India. These figures are roughly in line with those calculated by the Energy Transitions Commission (Energy Transitions Commission, 2023a). Figure 29 shows the distribution of net-zero investments. At the global level, the power sector must represent 70% of the investments with the following breakdown: 38% in power generation (green electricity), 26% in power networks (electricity infrastructure and grids), and 6% in power storage (electricity efficiency). If we include buildings (14%) and transport (8%), the figure is 92%. The remaining 8% concerns removals (waste management, recycling), hydrogen and finally industry. This confirms that all sectors are not equal in terms of net-zero investments.

Figure 29: Net-zero capital investments



Source: Energy Transitions Commission (2023a, page 9) & Authors' calculations.

Energy Transitions Commission (2023a) distinguishes between two types of financing: capital investment in technologies and assets, and grants to pay for the required measures. Capital investments are made by the private and public sectors and in most cases will generate future returns, while grants are made where there is no economic incentive to undertake a particular action related to early phase-out of coal, ending deforestation and carbon sequestration. The $3.5 trillion required will come from capital investment, with $0.5 trillion allocated to investments in fossil fuels that are destined to decline. Another challenge is scaling up in middle- and low-income countries. While we estimate that efforts in developed markets need to be multiplied by a factor of two, in middle- and low-income countries the factor is nearly seven.

As noted above[8], the power sector will require the largest investment of any sector, at $2.4 trillion per year, to finance carbon-free power generation, transmission and distribution networks, and to improve grid flexibility. Indeed, electrification will be a key part of the transition and will have spillover effects on other sectors of the economy. This will require a significant increase in global energy supply from 27 000 TWh to 130 000 TWh by 2050, including increases in wind and solar power, as well as other zero-carbon solutions such as hydropower. The buildings sector is the second largest sector requiring the most funding at $500 billion per year, followed by the transportation sector at $280 billion per year, and finally the carbon capture and storage, hydrogen, and industrial sectors at $135 billion, $80 billion, and $70 billion, respectively. While these investments are feasible from a macroeconomic perspective, they still require a significant increase in overall investment and a reallocation of capital in the 2020s. At the country level, this means that high-income countries will need to invest about $1,250 billion per year, double the current level. Middle-income countries will need $875 billion and low-income countries $25 billion, while China

[8] All figures in this paragraph are taken from the ETC report (Energy Transitions Commission, 2023a).

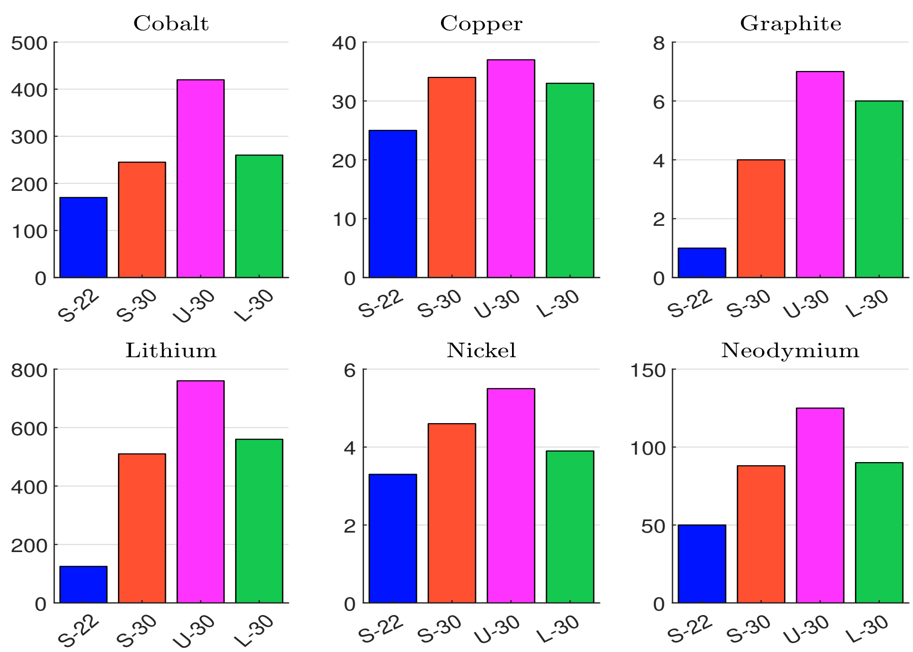
could achieve an additional investment of $700 billion.

Funding for the concessional payments, on the other hand, will come from a variety of sources: the carbon market through the purchase of carbon credits by companies, philanthropists committed to mitigation, and mostly from intergovernmental transfers. The ETC estimates the required payments at around $300 billion per year in 2030, of which $25-50 billion will be needed to phase out coal, $130 billion to end deforestation by 2030, and $100 billion to finance carbon sequestration (Energy Transitions Commission, 2023a).

3.1.2 Material and resource requirements

The transition to clean energy will place significant demands on a range of materials. Some are widely used in several clean technologies, such as steel, copper, aluminium, nickel and chromium, and some are needed for non-energy related technologies, such as steel for construction. Other materials are used in specific types of clean technologies, such as cobalt for electric vehicles and batteries and polysilicon for solar PV (Table 13). Up to 6.5 billion tonnes of materials could be needed cumulatively between 2022 and 2050 during the transition, with steel, copper and aluminium accounting for an estimated 95%. Currently available global mineral resources will be sufficient to meet demand until 2050, as new resources and reserves are expected to increase as demand grows. However, certain materials may become depleted and unable to meet cumulative demand. This can be addressed through technological innovation, the expansion of existing mines or the creation of new ones, as well as a significant increase in funding. But one of the most important measures is recycling. For cobalt, graphite and lithium, more than 50% of the energy transition needs could be met by recycled supply, while for copper and aluminium it's up to 30-40% (Energy Transitions Commission, 2023b).

Figure 30: Demand and primary supply in 2030



Source: Energy Transitions Commission (2023b), Material Factsheets.

Table 13: Mineral requirements for clean energy technologies

	Aluminium	Chromium	Copper	Cobalt	Graphite	Lithium	Neodymium
Bioenergy	◐	○	●	○	○	○	○
CSP	●	●	◐	○	○	○	○
Electricity Networks	●	○	●	○	○	○	○
EVs and Battery storage	●	○	●	●	●	●	●
Geothermal	○	●	○	○	○	○	○
Hydrogen	◐	○	○	○	○	○	○
Hydropower	◐	◐	◐	○	○	○	○
Nuclear	○	◐	◐	○	○	○	◐
Solar PV	●	○	●	○	○	○	○
Wind	◐	◐	●	○	○	○	●

	Nickel	Platinum	Polysilicon	REEs	Silver	Steel	Uranium	Zinc
Bioenergy	○	○	○	○	○	○	○	◐
CSP	◐	○	○	○	○	○	○	◐
Electricity Networks	○	○	○	○	○	●	○	○
EVs and Battery storage	●	○	○	●	○	○	○	○
Geothermal	●	○	○	○	○	○	○	○
Hydrogen	●	●	○	◐	○	●	○	○
Hydropower	○	○	○	○	○	●	○	◐
Nuclear	◐	○	○	○	○	●	●	○
Solar PV	○	○	●	○	●	●	○	○
Wind	◐	○	○	●	○	●	○	●

Source: ?, page 45 & Energy Transitions Commission (2023b, Exhibit 1.4, page 20).

Box 1: Supply and demand issues by materials

- Demand for steel and aluminium is largely driven by non-energy transition sources. Between 2022 and 2050, the cumulative demand for steel is 170 Mt, less than 10% of current annual production. On the other hand, aluminium demand averages 30 Mt, which is 30% of current annual production. The supply of steel and aluminium will increase steadily until 2030, with much of the supply coming from recycling. However, the production of steel and aluminium is very carbon intensive, so measures will need to be taken to decarbonize these materials.

- Demand for cobalt comes mainly from electric vehicles and is expected to increase 2-3 times by 2030. The current supply of 170 Kt, mainly from the Democratic Republic of Congo (70%), cannot meet the future demand of 420 Kt. Increased efficiency and new technologies could reduce demand by up to 40%, resulting in cobalt demand of 260 Kt in 2030. And supply could increase to 245 Kt due to expansion in Indonesia.

- Copper is probably the material with the highest demand, as it is required in most clean energy technologies. Current supply is less than the overwhelming future demand due to various challenges such as depletion of existing mines or even lack of investment to expand production. However, a potential shift could reduce copper demand by 4 Mt in 2030 (from 37 Mt to 33 Mt) and measures on recycling and efficiency can increase supply in 2030 and close the gap (34 Mt).

- Graphite is a key component in battery production. The increasing demand for batteries in the transition period makes the current supply very weak (1 Mt against 7 Mt). The possible use of silicon can help to slightly reduce the demand of 1 Mt. The supply gap can be closed somewhat by taking into account synthetic graphite, which will increase the graphite supply to 4 Mt in 2030, 40% lower than the lower bound demand of 6 Mt.

- Lithium demand is also a by-product of electric vehicle batteries and will increase to a demand of 760 Kt, completely overtaking the current supply of 125 Kt. The use of Na-ion chemistries and a shift in battery sizes could help reduce demand by 25% to 560 Kt. Global supply is expected to rise sharply to 510 Kt by 2030, which is better than current supply but still short of demand.

- Neodymium is used in permanent magnets for EV motors and wind turbines. The current supply of neodymium does not match the primary demand in 2030 (50 Kt in 2022 vs. 125 Kt in 2030), even taking into account the potential reduction of 30% due to new technologies. However, there is potential to close the gap between supply and demand with the new mining projects underway in several countries, leading to a supply of 88 Kt in 2030.

- Demand for nickel is high and diversified, ranging from electric vehicles and battery storage to geothermal and hydrogen electrolysis. The current supply of nickel does not match the growing demand, but the strong possibility of nickel-free batteries could help to reduce this demand from 5.5 Mt to 3.9 Mt in 2030 and allow supply (4.6 Mt) to overtake demand, thanks to the rapid and significant expansion of mining in Indonesia.

Source: IEA (2022a); Energy Transitions Commission (2023b), Material Factsheets.

In Figure 30, we show the demand and primary supply in 2030 calculated by Energy Transitions Commission (2023b). The legend is as follows: S-22 is the 2022 supply, S-30 is the projected 2030 supply, U-30 measures the 2030 primary demand including the energy transition demand, while L-30 is the 2030 primary demand assuming maximum efficiency and recycling improvements (Energy Transitions Commission, 2023b). An analysis by material is provided in Box 1. The supply/demand balance for copper and nickel appears to be achievable by 2030. For cobalt, lithium and neodymium, it can only be achieved by increasing efficiency and improving recycling.

The supply of materials can be threatened by many things, such as a lack of diversification in the mining, refining and processing stages. The mining stage is dominated by a handful of countries, such as the Democratic Republic of Congo for cobalt or China for rare earths. Concentration is more pronounced at the refining and processing stage, where China is largely dominant for five materials (cobalt, copper, lithium, nickel and rare earths). This increases the risk of supply disruptions due to political instability, geopolitical tensions or even physical risks (drought, etc.). The extraction and production of materials also has a significant impact on environmental and social issues, such as threats to local ecosystems and the risk of deforestation, concerns about pollution and toxicity, significant water consumption due to mining in arid areas, and the impact on local communities where good practices and workers' rights are not always respected.

3.1.3 Sector analysis

Below is a summary of funding needs by sector. All figures are taken from the ETC report (Energy Transitions Commission, 2023a).

Power According to Energy Transitions Commission (2023a), the three main challenges are an increase in total electricity supply from around 30 000 TWh today to over 100 000 TWh by mid-century, an extension of transmission and distribution networks from about 70 million km to up to 200 million km, and a green hydrogen production of 500-800 Mt per year.

Buildings The buildings sector requires initiated transition in the power sector to become green. We need to retrofit older buildings and create new carbon-efficient buildings. The $500 bn per year invested in the buildings sector will go towards upgrading buildings to incorporate new green technologies ($230 bn), purchase renewable heat ($130 bn) and install new heat pumps ($150 bn).

Mobility The investment required for the transition in the transport sector falls into 3 categories. The largest part of the transition from ICE (internal combustion engines) to EVs will require $130 bn per year to develop charging and refuelling facilities. Then $70 bn will be spent on sustainable aircraft manufacturing facilities and aircraft batteries. Finally, $40 bn will be spent on greening the shipping system through new infrastructure, vessels and investments.

Sustainable agriculture and land use requirements Most of the land is used for agriculture, but it is still needed to support wind and solar farms. The demand for wind and solar farms is far greater than the previous demand based on the fossil fuel system, but still far less than the demand for agriculture. Agriculture is the largest driver of deforestation and will need to change, taking into account new greenhouse gas efficient farming practices and changes in consumer behaviour.

Hydrogen Hydrogen will be used in many parts of the transition process. The \$80 bn investment will be allocated to the production and distribution of hydrogen. Of this, \$40 bn will be used to produce green and blue hydrogen and to recycle grey hydrogen. The remaining \$40 bn will help build pipelines, refuelling stations, exchange terminals and storage capacity.

Industry The industrial sector is plagued by carbon-intensive materials such as steel and cement, which need to be decarbonised through the use of CCS facilities, conversion processes, etc. Of the \$70 bn investment, \$10 bn will be used to decarbonise steel, \$10 bn for cement plants, \$40 bn to fully develop and integrate CCS and other decarbonisation technologies, and \$10 bn to deploy low-carbon technologies in smelters and refineries.

Waste management and circular economy Waste management is an important action to consider when talking about the transition to a low-carbon economy. Waste is generated at every stage of the transition, from food waste from agriculture to waste from solar panels, wind farms or even mining. According to the Energy Transitions Commission (2023b), the energy transition will generate up to 13 billion tonnes of waste from all materials by 2050. Various solutions can be proposed to manage waste and create a more circular economy, the most important of which is to introduce recycling, which not only helps to reduce waste but also increases the supply of materials. McKinsey (2022) also suggests other solutions, such as providing landfill space for organic waste, investing in digesters and composters, or even introducing new technologies to capture methane.

Water management According to Energy Transitions Commission (2023b), global water consumption will be 4 000 billion m^3 per year in 2050, of which 70% is used for agriculture (2 800 billion m^3), 58 billion m^3 for clean energy production and 37 billion m^3 for fossil fuels. For clean energy production, we see that water is used for nuclear power generation (14 billion m^3 per year), hydrogen production by electrolysis (11 billion m^3 per year), carbon capture (19–29 billion m^3 per year) and cleaning solar panels. This is in addition to the approximately 4 billion m^3 per year used for mining. This critical demand for water for energy production could increase water stress and scarcity. There are a number of solutions that need to be applied to alleviate water stress, such as trying to reduce its use as much as possible (especially for mining), or at least improving the efficiency of water use, and looking at ways to get more water, such as desalination or recycling. Energy and water are closely linked: the energy sector needs water for its clean energy transformation, while the water sector also needs energy for development, water recycling, desalination, transport or even distribution, with global energy use in the water sector expected to double by 2040 (IEA, 2017).

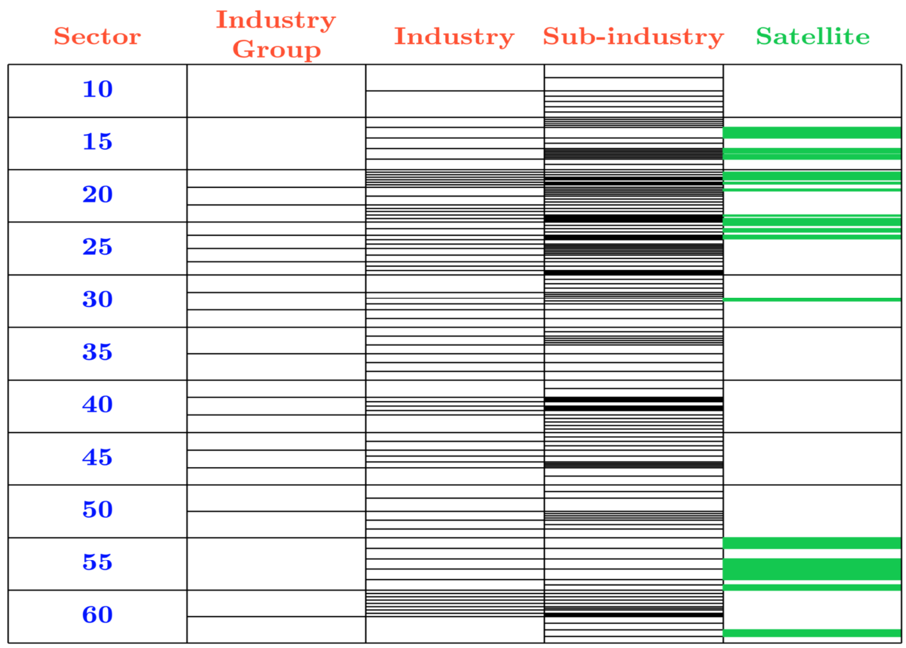
3.1.4 Narrow definition of the satellite investment portfolio

The previous analysis shows that the list of main sectors financed is relatively small. To get a better idea, we have mapped the previous activities to level 4 of the GICS classification. The results are presented in Table 14. In fact, we identify 29 sub-industries out of the 163 included in the GICS classification. Looking at the main sub-industries that can be included in the net-zero satellite portfolio, four of the 11 GICS sectors are over-represented, two are included and the other five are excluded. The four over-represented sectors are Industrials, Materials, Consumer Discretionary and Utilities. The Industrials sector is divided into three industry groups: Capital Goods, which includes sub-industries related to machinery, equipment and construction; Transportation, where we look at how to improve public transport

Table 14: Main sub-industries of the net-zero satellite portfolio (GICS level 4)

Code	Level 4	Level 2	Level 1
15102010	Construction Materials	Materials	Materials
15104010	Aluminium		
15104020	Diversified Metals & Mining		
15104025	Copper		
15104040	Precious Metals & Minerals		
15104045	Silver		
15104050	Steel		
20102010	Building Products	Capital Goods	Industrials
20103010	Construction & Engineering		
20104010	Electrical Components & Equipment		
20104020	Heavy Electrical Equipment		
20106010	Construction Machinery & Heavy Transportation Eqpt.		
20106015	Agricultural & Farm Machinery		
20201050	Environmental & Facilities Services	Commercial & Professional Services	
20304010	Rail Transportation	Transportation	
20305010	Airport Services		
20305020	Highways & Railtracks		
20305030	Marine Ports & Services		
25101010	Automotive Parts & Equipment	Automobiles & Components	Consumer Discretionary
25102010	Automobile Manufacturers		
25201010	Consumer Electronics	Consumer Durables & Apparel	
25201030	Homebuilding		
25201040	Household Appliances		
30202010	Agricultural Products	Services Food, Beverage & Tobacco	Consumer Staples
55101010	Electric Utilities	Utilities	Utilities
55103010	Multi-Utilities		
55104010	Water Utilities		
55105020	Renewable Electricity		
60201030	Real Estate Development	Real Estate Management & Development	Real Estate

Figure 31: Narrow specification of the satellite investment universe



systems and their infrastructure; and finally Commercial & Professional Services with the Environmental & Facilities Services sub-industry, which mainly covers waste management and pollution. The Materials sector is characterised by the various materials used in the energy transition, such as aluminium, copper, steel, etc. The Consumer Discretionary sector is divided into two industry groups, Automobiles & Components, where we find automobile manufacturers and automotive parts, and Consumer Durables & Apparel, related to home building and appliances. Finally, the Utilities sectors will show different types of utilities needed for the transition, such as electric utilities, water utilities or even renewable electricity. Then we include two sub-industries that belong to consumer staples and real estate sectors respectively, agricultural products and real estate development. To summarize, this means that not all the sectors are represented. In Figure 31, we have drawn the four levels of the GICS classification and indicated which sub-industry falls within this narrow definition of the satellite investment universe.

Remark 5. *It is clear that the GICS classification is not relevant when considering a net-zero investing framework. For example, there is no sector such as electricity storage, hydrogen storage, photovoltaic electricity generation, wind electricity generation, nuclear electricity generation in existing plants, etc. Nevertheless, this is the classification used by investors.*

3.1.5 Relationship with green taxonomies

As the need to go green increases, financial institutions need to be able to identify which economic activities will have a positive impact on the transition and make decisions accordingly. The European Union has created a classification scheme to help catalogue which activities are sustainable by introducing six objectives: climate change mitigation, climate change adaptation, sustainable use and protection of water and marine resources, transition

Figure 32: EU taxonomy

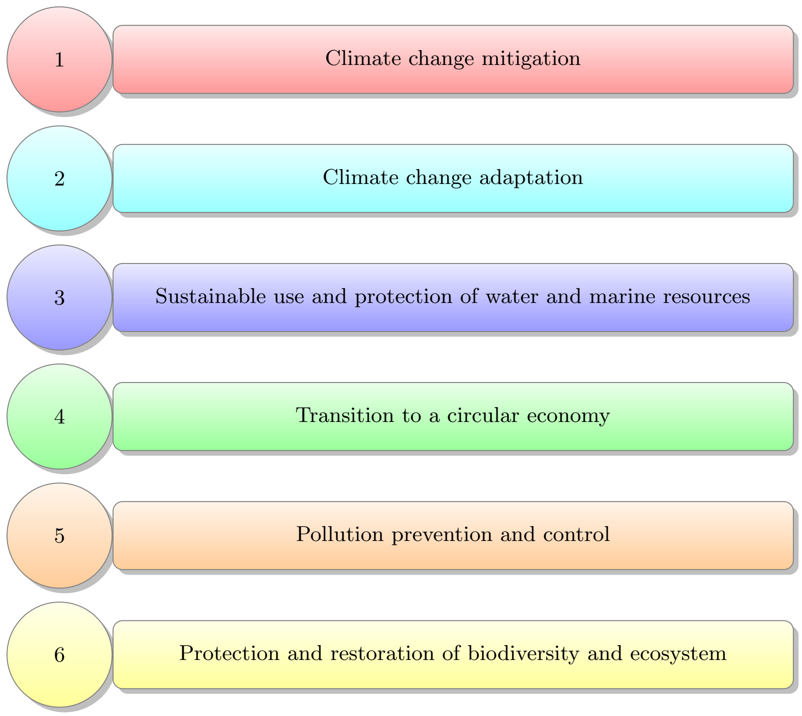
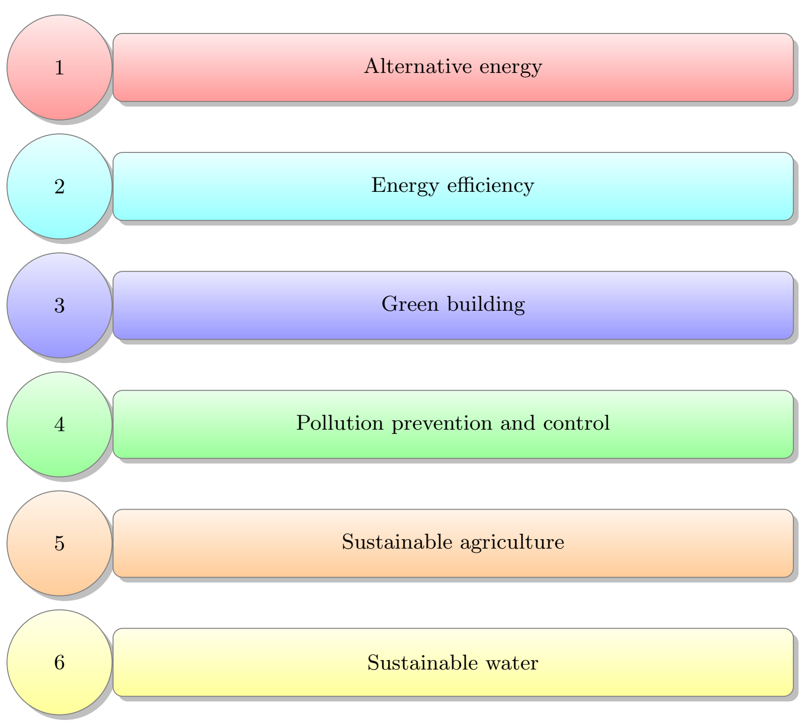


Figure 33: MSCI taxonomy



to a circular economy, pollution prevention and control, protection and restoration of biodiversity and ecosystems (Figure 34). In addition to these objectives, there are also four conditions that must be met: the activity must make a significant contribution to at least one environmental objective, must not significantly harm the other objectives, must respect minimum safeguards and must meet the technical screening criteria. The use of a taxonomy[9] is important when building the satellite portfolio.

The green taxonomy can be seen as a broad definition of the satellite investment portfolio. In fact, it includes some activities that are considered green but are not critical to achieving net-zero and reaching a low-carbon economy. More precisely, the taxonomy defines two classification categories: enabling activities and transitional activities. The EU taxonomy therefore aims to include not only activities that are already green, but also activities that are on a transition path and activities that enable others to exist, such as essential parts of their supply chain. For example, the production of cement, iron and steel are transitional activities, while libraries, archives, museums and cultural activities are enabling activities. Cement, iron and steel are brown today, but we hope they will be green in the future. Libraries, archives, museums and cultural activities are already considered green. In this context, it is clear that the green taxonomy and net-zero financing are two different concepts, but that they are inextricably linked. Indeed, the scope of the green taxonomy is broader than the scope of net-zero financing.

3.1.6 Tracking net-zero progress

In July 2023, the International Energy Agency published a report tracking the progress of clean energy in 2023 across 50 components (Tables 15 and 16). Only 3 are on track according to the Net Zero by 2050 scenario: Solar PV in the electricity sector, electric vehicles in the transport sector and lighting in the buildings sector. Solar PV is characterised by annual growth of 26% in 2022, while electric vehicles have a sales surge of 55% in the same year. Although not many components are '*on track*', progress is clearly being made in parts of the energy systems. This is largely due to the availability of clean technologies and their falling costs. However, progress remains uneven across regions and sectors. For example, most electric vehicle sales and carbon capture capacity are in China, the US and Europe.

Table 15: What's on track (energy system overview)

Energy Efficiency	
Behavioural Changes	
Electrification	
Renewables	
Bioenergy	
Hydrogen	
Carbon Capture, Utilisation and Storage	
Innovation	
International Collaboration	
Digitalisation	

[9] Other taxonomies exist such as the MSCI taxonomy, which classifies economical activities into six categories: alternative energy, energy efficiency, green building, pollution prevention and control, sustainable agriculture and sustainable water (Figure 35).

Table 16: What's on track (sector analysis)

Transversal Technologies & Infrastructure	🟡	Electricity	🟡
CO_2 Transport and Storage	🔴	Coal	🔴
CO_2 Capture and Utilisation	🟡	Natural Gas	🟡
Bioenergy with Carbon Capture and Storage	🔴	Solar PV	🟢
Direct Air Capture	🟡	Wind	🟡
Electrolysers	🟡	Hydroelectricity	🟡
District Heating	🔴	Demand Response	🟡
Data Centres and Transmission Networks	🟡	Nuclear Power	🟡
Transport	🔴	Grid-scale Storage	🟡
Cars and Vans	🟡	Smart Grids	🟡
Trucks and Buses	🔴	Energy	🔴
Rail	🟡	Oil & Natural Gas Supply	🔴
Aviation	🔴	Methane Abatement	🔴
International Shipping	🔴	Gas Flaring	🔴
Electric Vehicles	🟢	Biofuels	🔴
Industry	🔴	Buildings	🟡
Steel	🔴	Heating	🟡
Chemicals	🔴	Space Cooling	🟡
Cement	🔴	Lighting	🟢
Aluminium	🔴	Appliances & Equipment	🟡
Paper	🔴	Building Envelopes	🔴
Light Industry	🟡	Heat Pumps	🟡

🟢 on track, 🟡 more efforts needed, 🔴 not on track

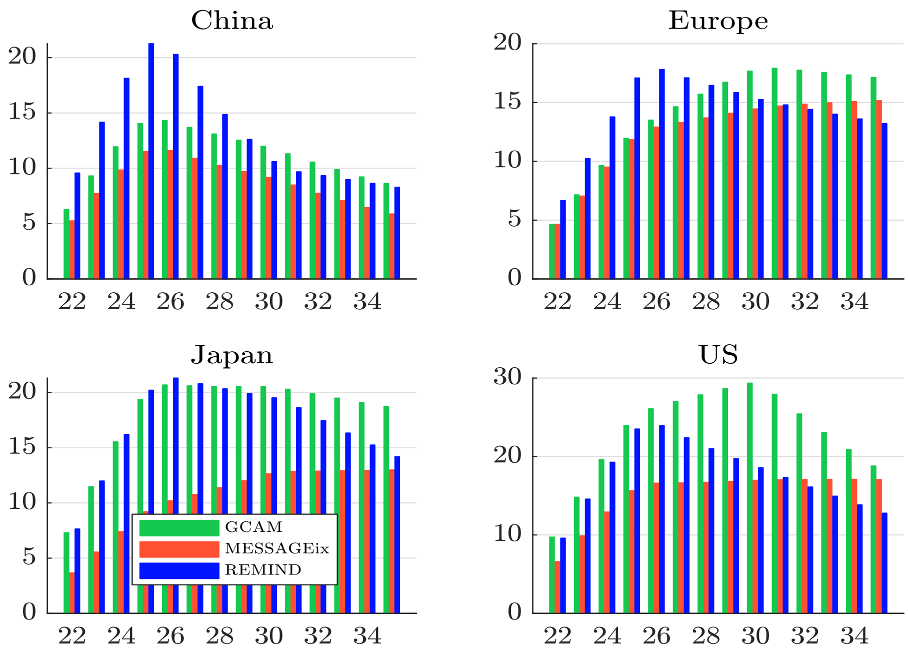
Source: IEA (2023).

3.1.7 Public vs. private investments

The question now is who will finance the \$3.5 trillion of new net-zero investment? In other words, how much will come from public investment and how much from private investment? To answer this question, we use the latest NGFS scenarios. In particular, we calculate the relative difference in % between investment in the net-zero scenario and the baseline scenario. Figure 34 shows the public investment while Figure 35 shows the private investment[10]. We find that the estimates depend on the model. On average, public investment in China, Europe and Japan increases by between 5% and 20% per year. In the US, the increase in public investment could reach 30% per year. In contrast, private investment is lower in the net-zero scenario than in the baseline scenario. These results are disturbing because they give the impression that the transition is being financed by the public rather than the private sector. To understand these figures, we need to analyze the financing conditions. We observe a global increase in inflation of between 0.5% and 3% per year. At the same time, long-term interest rates increase between 0.5% and 1.5% per year. Therefore, there may be a trade-off between the return on public debt and the return on private investment, and the huge increase in capex may be a negative factor in stimulating private investment.

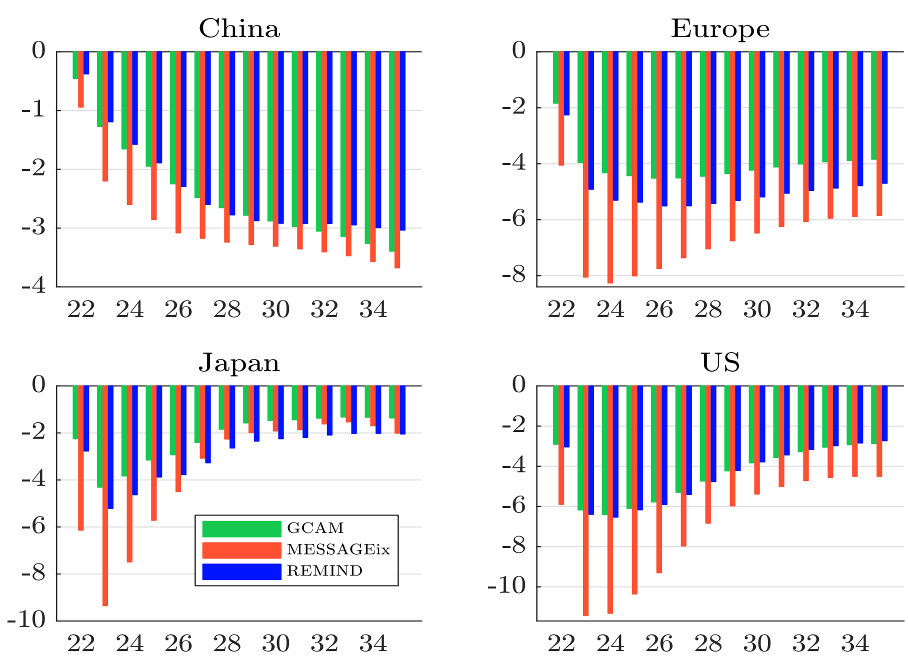
[10] We consider the results of the combined physical and transition risk scenario. The corresponding NGFS variables are `NiGEM|Investment (gov.)|Combined` and `NiGEM|Investment (private sector)|Combined`.

Figure 34: Public investment – relative difference in % compared with the baseline scenario



Source: NGFS (2022) & https://data.ene.iiasa.ac.at/ngfs.

Figure 35: Private investment – relative difference in % compared with the baseline scenario



Source: NGFS (2022) & https://data.ene.iiasa.ac.at/ngfs.

3.2 Investment universe

How can investors participate in the net-zero journey? Table 17 shows the list of of financial instruments defined by Swiss Sustainable Finance to finance the net-zero transition. The list covers all financial institutions. It includes the banking system, the insurance sector, etc. We have indicated the instruments that concern the asset management industry. As shown above, a large part of net-zero will be financed by public debt. Sovereign green bonds would therefore be the main investment vehicle for investors. But they are not enough. Corporate green bonds must also form a significant part of the satellite portfolio. In addition to green bonds, investors need to consider other types of instruments, in particular direct or indirect investments in green infrastructure and sustainable real estate. Finally, they can invest in the equity market to support companies that make a significant contribution to the environment or are essential to the net-zero transition.

Table 17: Overview on financing instruments

	Instrument	AM		Instrument	AM
1	Thematic equity funds	✓	8	Venture capital investments	✓
2	Non-thematic listed equity and bond indices	✓	9	Insurances for energy efficiency and renewable energy	
3	Engagement for non-thematic listed equities and bonds	✓	10	Energy performance contracting (EPC)	
4	Green bonds	✓	11	Community finance: renewable energy cooperatives	
5	Sustainable real estate investments	✓	12	Carbon credit markets	
6	Energy efficiency mortgages		13	Blended finance	✓
7	Direct investments in non-listed companies and projects	✓	14	Green state investment bank	

Source: Swiss Sustainable Finance (2020, Table 1, page 9).

Green bonds are the main instrument for financing the net-zero transition. As such, they generally represent a larger allocation of the satellite portfolio in a multi-asset framework. Let α_{Equity} and α_{Bond} be the proportions of equities and bonds in the multi-asset investment portfolio. Let α be the weight of the satellite portfolio. The core allocation is given by the vector $\left(\alpha_{\text{Equity}}^{\text{Core}}, \alpha_{\text{Bond}}^{\text{Core}}\right)$, while the satellite allocation is defined by $\left(\alpha_{\text{Equity}}^{\text{Satellite}}, \alpha_{\text{Bond}}^{\text{Satellite}}\right)$. We have the following identities:

$$\alpha_{\text{Equity}} = (1-\alpha)\,\alpha_{\text{Equity}}^{\text{Core}} + \alpha\,\alpha_{\text{Equity}}^{\text{Satellite}}$$

and:

$$\alpha_{\text{Bond}} = (1-\alpha)\,\alpha_{\text{Bond}}^{\text{Core}} + \alpha\,\alpha_{\text{Bond}}^{\text{Satellite}}$$

We deduce that:

$$\alpha_{\text{Bond}}^{\text{Core}} = \frac{\alpha_{\text{Bond}} - \alpha\,\alpha_{\text{Bond}}^{\text{Satellite}}}{1-\alpha}$$

In Table 18, we report the values taken by $\alpha_{\text{Bond}}^{\text{Core}}$ when we target several constant-mix strategies (60/40, 50/50 and 20/80). We assume that $\alpha_{\text{Bond}}^{\text{Satellite}}$ is set to 70% or 90%. For example, if green bonds account for 70% of the satellite portfolio's allocation and the satellite has a weight of 25%, the core portfolio's bond allocation must be set at 30% to achieve a 60/40 constant-mix strategy.

Table 18: Calculation of $\alpha_{\text{Bond}}^{\text{Core}}$ (in %)

Strategy		60/40		50/50		20/80	
$\alpha_{\text{Bond}}^{\text{Satellite}}$		70.0	90.0	70.0	90.0	70.0	90.0
α	1%	39.7	39.5	49.8	49.6	80.1	79.9
	5%	38.4	37.4	48.9	47.9	80.5	79.5
	10%	36.7	34.4	47.8	45.6	81.1	78.9
	15%	34.7	31.2	46.5	42.9	81.8	78.2
	20%	32.5	27.5	45.0	40.0	82.5	77.5
	25%	30.0	23.3	43.3	36.7	83.3	76.7

3.2.1 Green bonds

The green bond label is attributed to "*any type of bonds instrument where the proceeds will be exclusively applied to finance or re-finance in part of full new and existing eligible green projects and which are aligned with the four core components of the Green Bond Principles*" (ICMA, 2021). To ensure market integrity and avoid greenwashing, the ICMA proposes a set of four core guidelines: the use of proceeds, the project evaluation and selection process, the management of proceeds and reporting. The first and arguably most important guideline of the GBPs is to establish a list of eligible projects to which the proceeds should be allocated. Here is an overview of the most important projects:

- Energy: expand the production and the transmission of renewable energy and accelerate energy efficiency;
- Sustainable infrastructure: development of clean transport and clean buildings;
- Biodiversity: conservation of terrestrial and aquatic biodiversity;
- Climate change: development of adaptation and mitigation solutions;
- Sustainable industry: prevention and control over pollution;
- Resources: preserve living natural resources and sustainable management of land use, water and sanitation;
- Circular economy: improving production and the processes of eco-efficient products.

The second principle requires a transparent and clear project evaluation and selection process by the issuer. The third principle deals with the management of the proceeds and the final principle sets out a reporting standard. Similar principles have been developed for the other types of sustainable bonds (social, sustainability and sustainability-linked bonds). These four types of bonds[11] make up the GSS+ investment universe (Roncalli, 2023).

We have obtained data from Bloomberg to describe the GSS+ investment universe. For each bond, Bloomberg indicates whether it is a green, social, sustainability, sustainability-linked or conventional bond. Issue amounts are shown in Table 19. In 2022, 1 784 green bonds were issued for a total of \$531.6 bn. This represents 15% of the net-zero funding requirement. For the other categories, the amount issued in 2022 is equal to \$152.8 bn for social bonds, \$174.8 bn for sustainability bonds and \$144.3 bn for sustainability-linked bonds respectively. As explained by Ben Slimane *et al.* (2023), social bonds are not net-zero transition instruments, but more conventional bonds to finance social debt and social

[11] We use the following symbols to distinguish these bonds: GB for green bonds, SB for social bonds, SuB for sustainability bonds and SLB for sustainability linked bonds.

infrastructure. Therefore, if we look at a broad definition of the net-zero fixed income universe (GB + SuB + SLB), we get a total of \$850.7 bn, which can be seen as the upper bound of current investment opportunities. This is less than 25% of the \$3.5 tn previously required to achieve net-zero.

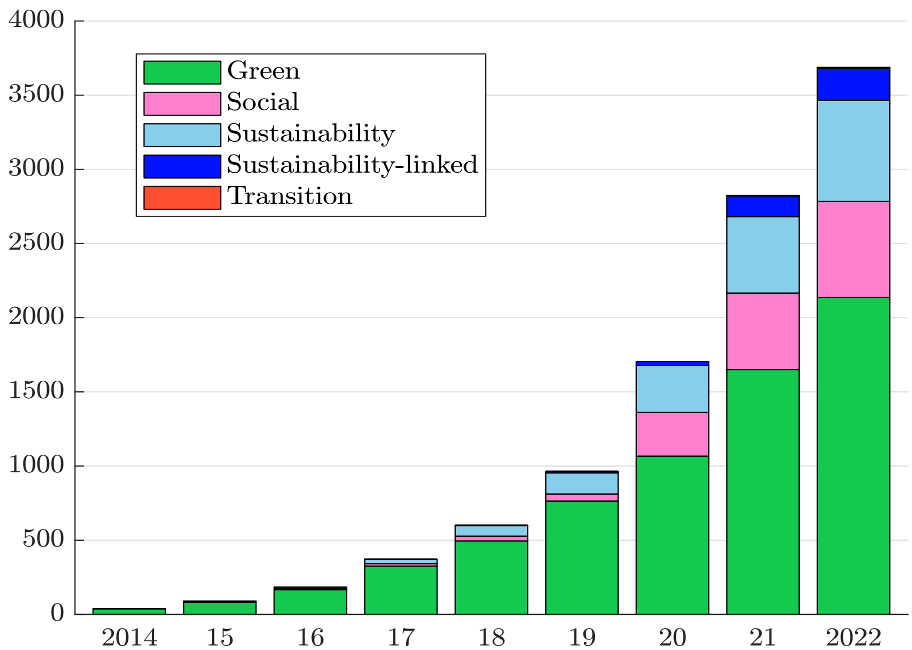
Table 19: GSS+ bond issuance

Year	GB		SB		SuB		SLB	
	#	\$ bn	#	\$ bn	#	\$ bn	#	\$ bn
2022	1 784	531.6	542	152.8	614	174.8	382	144.3
2021	1 971	686.1	554	242.1	646	233.2	343	161.5
2020	1 076	291.2	273	172.0	308	154.8	47	16.5
2019	877	268.0	99	22.2	333	85.2	18	8.9
2018	582	165.3	48	16.5	52	22.1	1	2.2
2017	472	160.9	46	11.8	17	9.2	1	0.2
2016	285	99.7	14	2.2	16	6.6	0	0.0

Source: Bloomberg, GSS+ Instrument Indicator

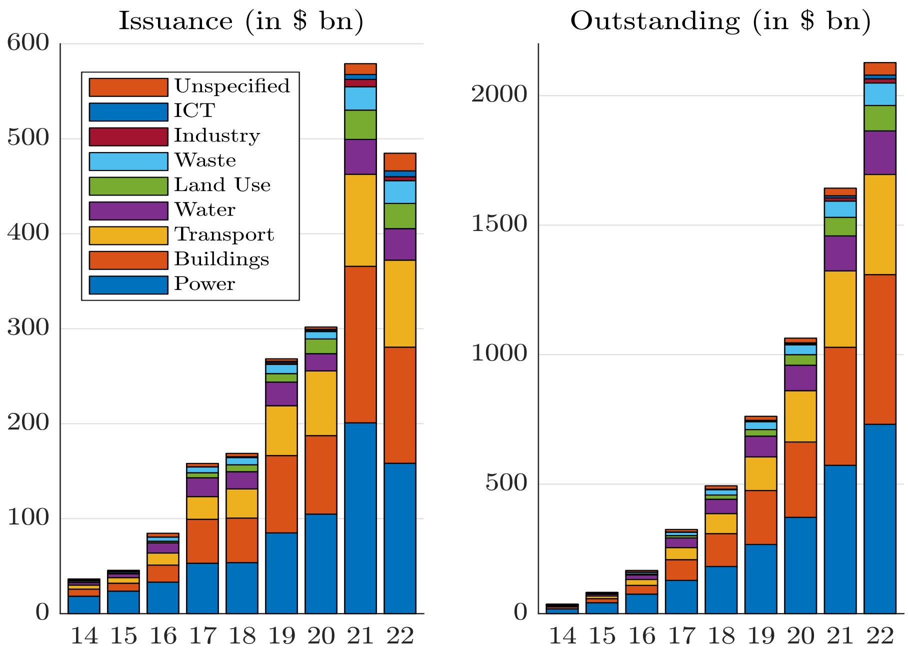
Remark 6. *The previous figures are certainly overestimated, as some bonds do not actually finance the transition. For example, if we look at the CBI database, which is more restrictive in its selection of sustainable projects, we get an amount of \$487.1 bn for the green bond investment universe and a total of \$724.8 bn for the broad measure. This represents* 20.7% *of the \$3.5 tn required to achieve net-zero. According to CBI (2023), by the end of 2022, GSS+ debt instruments have recorded a cumulative volume of* \$3.7 *tn. The evolution of notional outstanding is reported in Figure 36.*

Figure 36: Notional outstanding of GSS+ debt (in \$ bn)



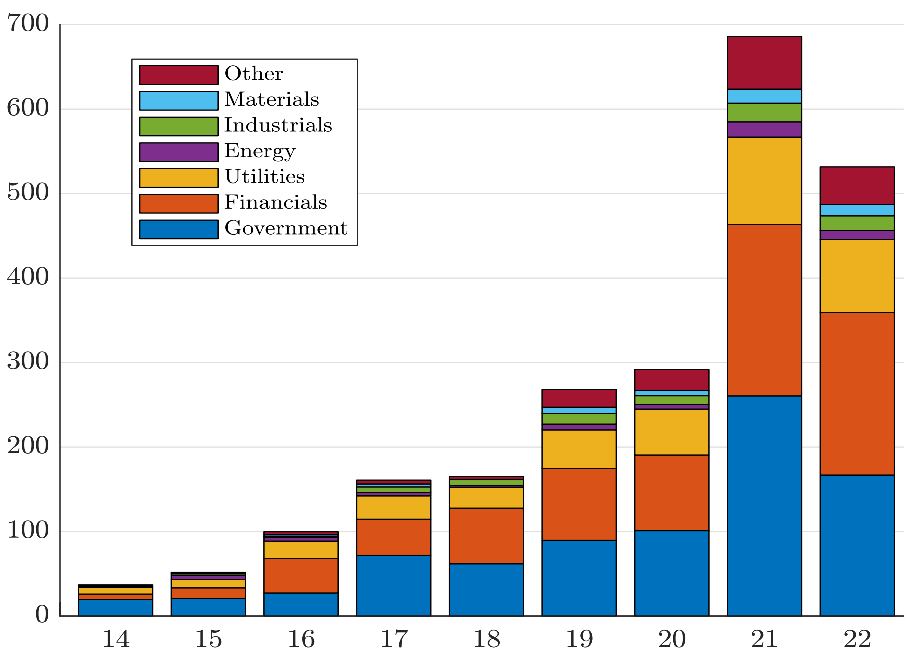
Source: https://www.climatebonds.net/market/data.

Figure 37: Issuance and notional outstanding of green bonds by use of proceeds



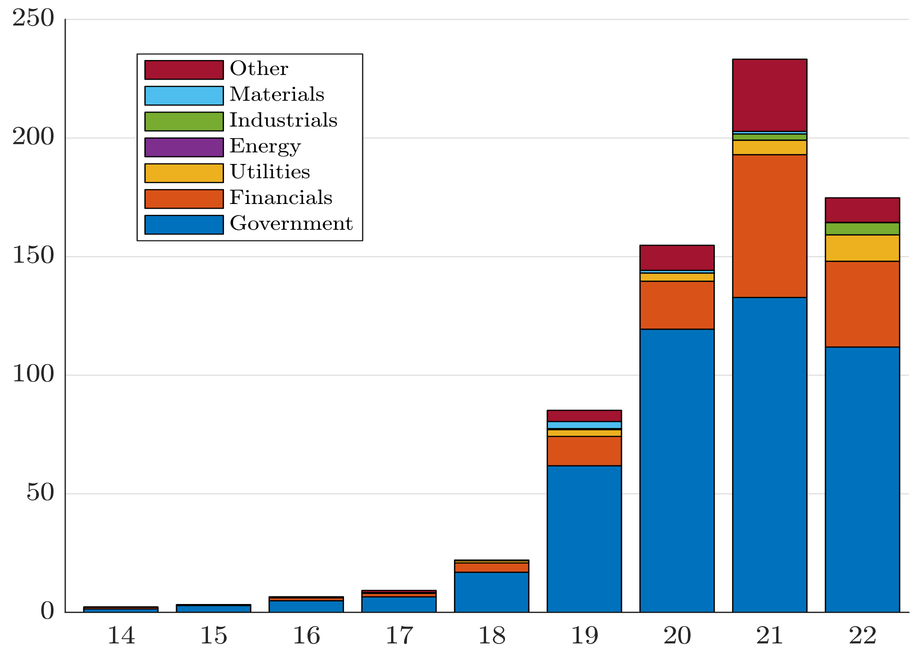
Source: https://www.climatebonds.net/market/data.

Figure 38: Issuance of green bonds by sectors



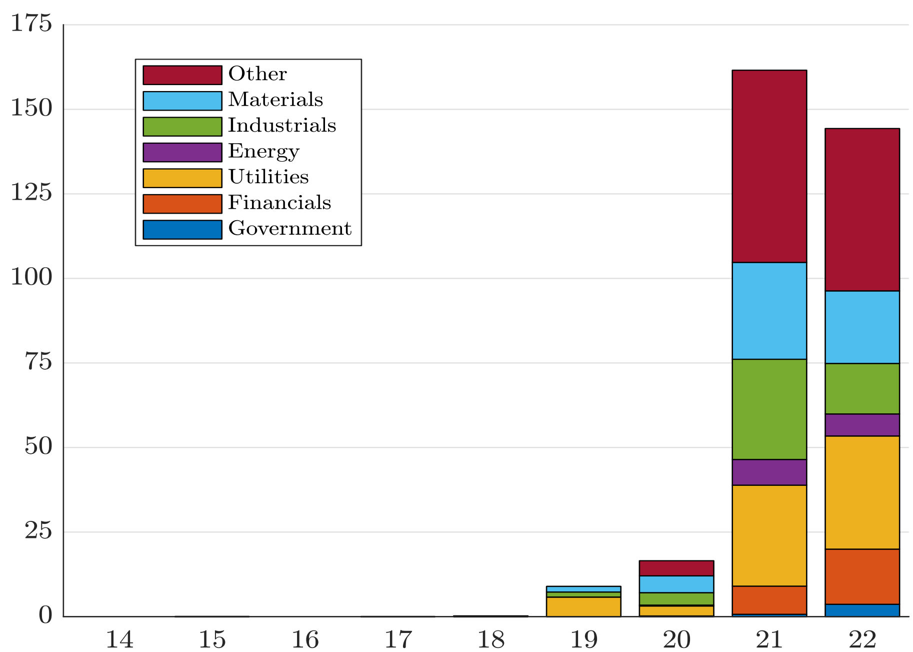
Source: Bloomberg, GSS+ Instrument Indicator.

Figure 39: Issuance of sustainable bonds by sectors



Source: Bloomberg, GSS+ Instrument Indicator.

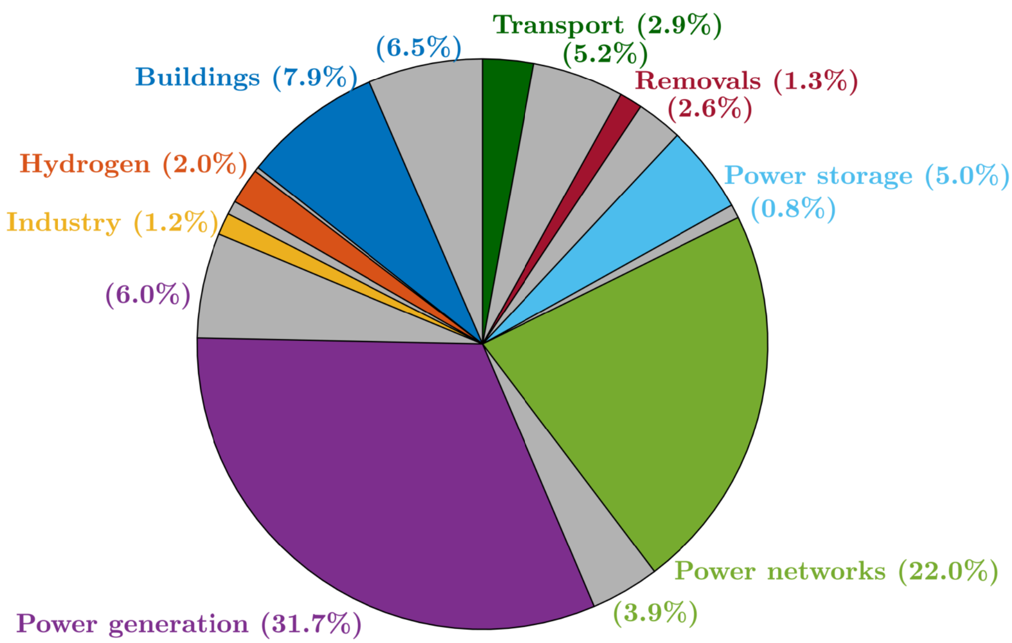
Figure 40: Issuance of sustainable-linked bonds by sectors



Source: Bloomberg, GSS+ Instrument Indicator.

The question of what GSS+ bonds finance is of central importance. Figure 37 shows the breakdown of green bonds by use of proceeds. On average, 35% of green bonds relate to the energy sector, 27% to buildings, 18% to transport and 12% to water management and land use. If we look at the distribution by sector, we get a different story (Figures 38, 39 and 40). If we aggregate green, sustainability and sustainability-linked bonds, we get the following figures: 39% for government, 27% for financials, 15% for utilities, 5% for industrials and 4% for materials. If we analyze the GSS+ bonds issued by government and financials, they are mainly in net-zero infrastructure, i.e. energy, transportation and buildings. Figure 41 is a new version of the net-zero capital investment shown in Figure 29. We have colored in gray the estimated share of investment financed by the GSS+ bond market[12]. This can help build the remaining satellite portfolios, including equity, infrastructure and real estate.

Figure 41: What the GSS+ bond market does and does not finance



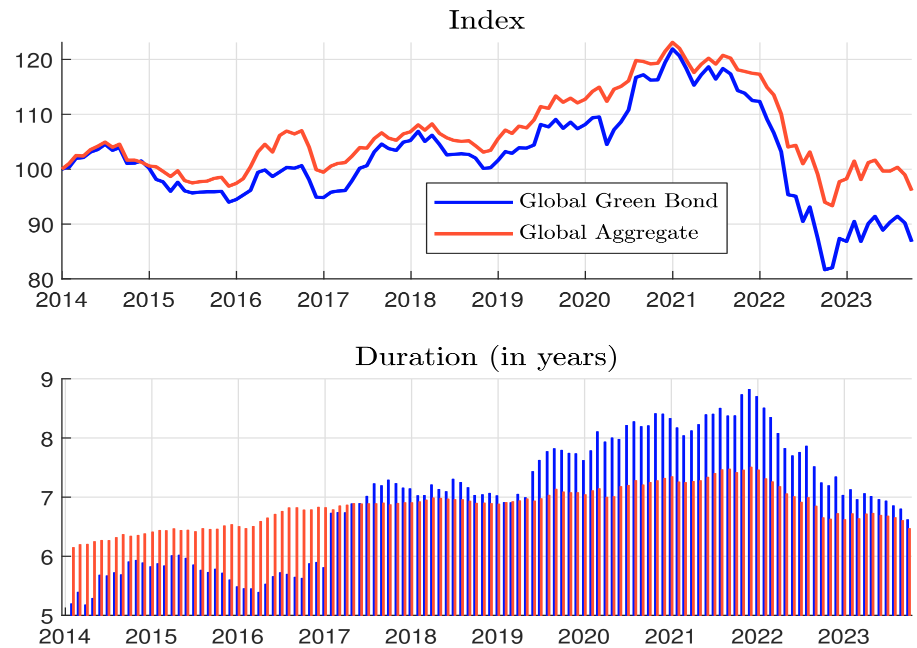
Source: Authors' calculations.

In Figure 42, we compare the performance of the Bloomberg Global Green Bond index to the performance of the Bloomberg Global Aggregate index. We see that there is a high tracking risk. Between January 2014 and September 2023, the tracking error is 2.7%. Several factors explain this high figure: sector allocation, duration, credit risk, etc. Investors must therefore accept a higher active risk for the satellite portfolio than for the core portfolio.

Let $R\left(x^{\text{Core}}\right)$, $R\left(x^{\text{Satellite}}\right)$, and $R(b)$ be the returns of the core, satellite and benchmark portfolios. The total portfolio is equal to $x = (1-\alpha)\, x^{\text{Core}} + \alpha x^{\text{Satellite}}$ where α is the proportion of the satellite portfolio. Since we have $R(x) - R(b) = (1-\alpha)\left(R\left(x^{\text{Core}}\right) - R(b)\right) + \alpha\left(R\left(x^{\text{Satellite}}\right) - R(b)\right)$, we deduce that the tracking error variance of the portfolio x is

[12] We assume that \$900 bn are financed through the GSS+ fixed-income market with the following allocation: 25% in buildings, 23% in power generation, 20% in transport, 15% in power networks, 10% in removals, 3% in power storage, 3% in industry, and 1% in hydrogen.

Figure 42: Performance and duration of the Bloomberg Global Green Bond and Aggregate indices



Source: Bloomberg (2023).

equal to:

$$\begin{aligned}\sigma^2\left(x \mid b\right) &= (1-\alpha)^2\,\sigma^2\left(x^{\text{Core}} \mid b\right) + \alpha^2\sigma^2\left(x^{\text{Satellite}} \mid b\right) + \\ &\quad 2\alpha\,(1-\alpha)\,\rho\left(x^{\text{Core}}, x^{\text{Satellite}} \mid b\right)\sigma\left(x^{\text{Core}} \mid b\right)\sigma\left(x^{\text{Satellite}} \mid b\right)\end{aligned}$$

where $\sigma\left(x^{\text{Core}} \mid b\right)$ and $\sigma\left(x^{\text{Satellite}} \mid b\right)$ are the tracking error volatilities of x^{Core} and $x^{\text{Satellite}}$, and $\rho\left(x^{\text{Core}}, x^{\text{Satellite}} \mid b\right)$ is the correlation between the excess returns $R\left(x^{\text{Core}}\right) - R\left(b\right)$ and $R\left(x^{\text{Satellite}}\right) - R\left(b\right)$. Let us apply the previous formula to the universe of bonds. Assuming $\sigma\left(x^{\text{Core}} \mid b\right) \approx 1\%$ and $\sigma\left(x^{\text{Satellite}} \mid b\right) \approx 3\%$, we expect the bond allocation to generate a tracking error volatility between 1% and 1.5% for reasonable values of α and $\rho\left(x^{\text{Core}}, x^{\text{Satellite}} \mid b\right)$.

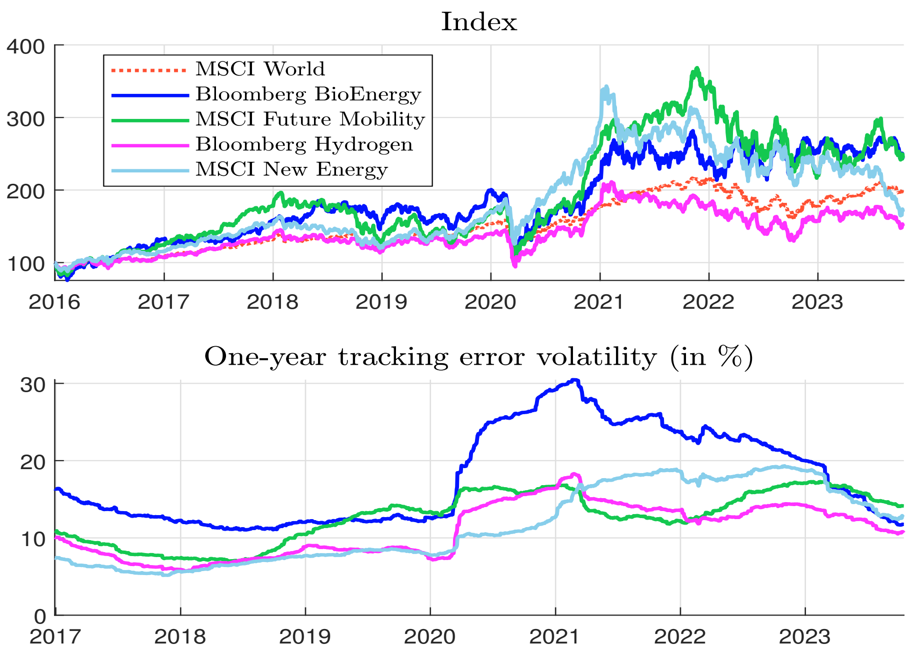
3.2.2 Green stocks

We can invest in green stocks using thematic funds focusing on a specific subject or an equity basket. Generally, the second approach is generally implemented by equity managers while the first approach is preferred by other fund managers, especially multi-asset managers.

Thematic equity funds The emergence of economic, social and technological megatrends is strongly influencing the expansion of thematic funds. Some funds address the environmental challenge with a broader range of climate actions and solutions, investing only in companies with the best environmental practices and goals. These funds are not necessarily focused on net-zero transition. However, they generally include renewable energy stocks.

Some more specific thematic funds have been developed to address net-zero issues such as clean energy, hydrogen, water management, and future mobility. Figure 43 shows the performance of four thematic equity indices: Bloomberg BioEnergy, Bloomberg Hydrogen, MSCI Future Mobility and MSCI New Energy. We find that these indices have a high risk of tracking error relative to the MSCI World Index. On average, we can assume that the tracking error volatility of the satellite equity portfolio is around 20%.

Figure 43: Performance and tracking error volatility of thematic equity indices



Source: Bloomberg (2023) & MSCI (2023).

Equity basket The fund manager can also develop a stock picking process related to the net-zero topic. In this case, he can build a screening based on green revenue share, green capex or green opex measures. The green revenue share measure presented by Barahhou *et al.* (2022) assess the revenue deduced from sustainable activities. Green capex measures the investment spending towards green and sustainable activities, while green opex consider the expenses needed to carry out a green activity by the issuer. More generally, the underlying idea for building a satellite equity portfolio with a basket of stocks is to select stocks according to a green intensity measure, which may be aligned with the EU taxonomy.

Consider the narrow specification of the satellite investment universe defined in Table 14 and Figure 31. Using the MSCI World index universe, we have assigned each stock to its sub-industry. In Table 20, we calculated the percentage (adjusted for weight in the MSCI World) of stocks that fit the narrow definition. For example, 28.62% of the Consumer Discretionary sector is aligned to the narrow specification. In total, this represents 11.37% of the market capitalisation of the MSCI World index. Breaking this down, we see that the largest contributor is the Industrials sector with 35%, followed by the Consumer Discretionary sector (30.9%) and the Utilities sector (22.3%). This breakdown is far from the target allocation for the satellite equity portfolio.

Table 20: Statistics of the narrow definition (MSCI World, Dec. 2021)

Sector	Code	MSCI World			Satellite
		CW	Alignment	Breakdown	Target
Communication Services	50	8.35%			
Consumer Discretionary	25	12.25%	28.62%	30.9%	5 – 15%
Consumer Staples	30	6.91%	1.32%	0.8%	0 – 5%
Energy	10	3.12%			
Financials	40	13.16%			
Health Care	35	12.62%			
Industrials	20	10.21%	38.97%	35.0%	10 – 20%
Information Technology	45	23.68%			
Materials	15	4.10%	29.42%	10.6%	5 – 15%
Real Estate	60	2.79%	1.32%	0.3%	0 – 5%
Utilities	55	2.74%	92.80%	22.3%	50 – 70%
Total			11.37%	100.0%	

Source: MSCI (2023) & Authors' calculations.

Table 21: Average green intensities in % (MSCI World, Dec. 2021)

Sector	Code	Revenue	Capex	Opex	$\mathcal{GRS}$
Communication Services	50	0.07	0.02	0.02	2.79
Consumer Discretionary	25	0.25	0.98	0.89	19.59
Consumer Staples	30	0.00	0.40	0.00	0.85
Energy	10	0.57	2.46	1.06	4.79
Financials	40	0.01	0.03	0.02	0.77
Health Care	35	0.00	0.07	0.00	1.52
Industrials	20	1.98	2.21	2.34	22.86
Information Technology	45	0.02	0.04	0.02	13.28
Materials	15	0.26	0.92	0.59	15.41
Real Estate	60	0.56	1.33	0.55	21.18
Utilities	55	7.08	15.46	11.13	28.88
Total		0.48	0.97	0.73	10.64

Source: MSCI (2023) & Authors' calculations.

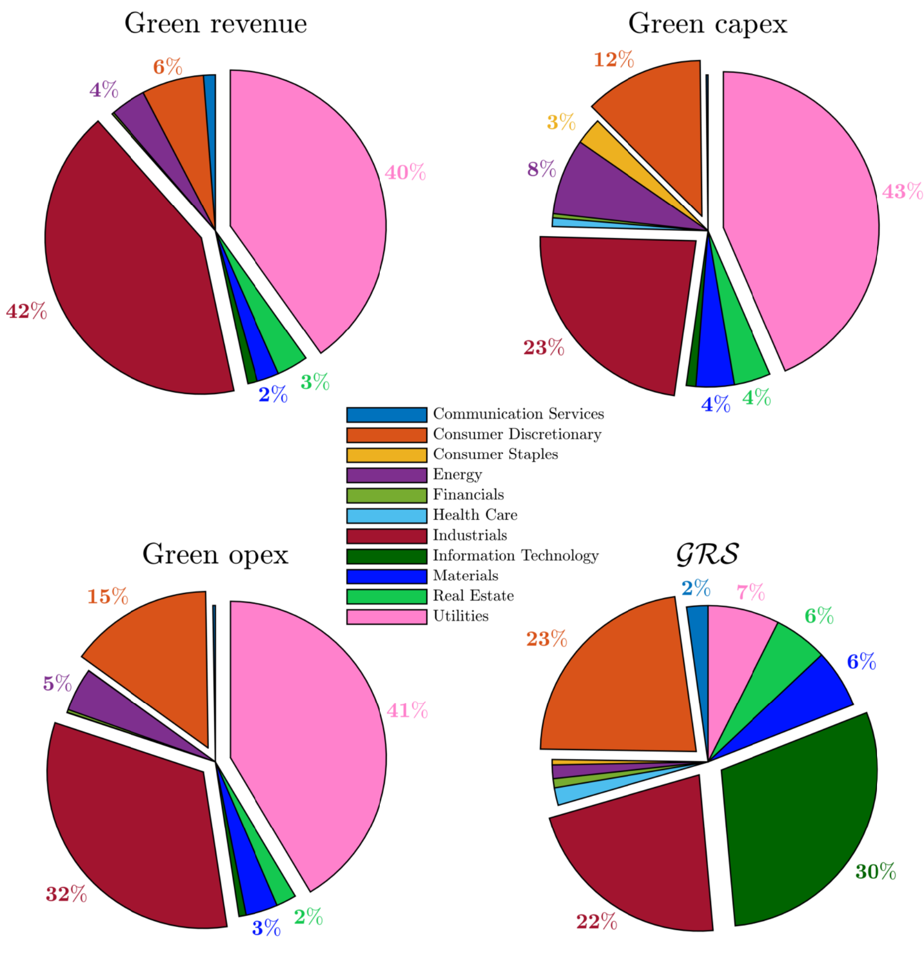
Table 22: Breakdown in % of green intensities (MSCI World, Dec. 2021)

Sector	Code	Revenue	Capex	Opex	$\mathcal{GRS}$
Communication Services	50	1.22	0.19	0.25	2.19
Consumer Discretionary	25	6.41	12.34	14.80	22.57
Consumer Staples	30	0.01	2.81	0.02	0.55
Energy	10	3.66	7.91	4.50	1.41
Financials	40	0.21	0.44	0.30	0.95
Health Care	35	0.00	0.89	0.04	1.80
Industrials	20	41.82	23.21	32.50	21.95
Information Technology	45	1.01	0.99	0.74	29.57
Materials	15	2.29	3.94	3.34	6.04
Real Estate	60	3.23	3.80	2.08	5.55
Utilities	55	40.14	43.49	41.43	7.43
Total		100.00	100.00	100.00	100.00

Source: MSCI (2023) & Authors' calculations.

In Table 21, we have calculated the average green intensity by sectors, weighted by the market capitalization. If we look at the entire universe of the MSCI World index, the green revenue aligned with the EU taxonomy is equal to 48 bps. Utilities is the sector with the highest green revenue, with an average of 7.08%. With the exception of Industrials, the average green revenue in the other sectors is less than 1%. The figures for capex and opex aligned with the EU taxonomy are better. We have also reported the results taking into account the green revenue share ($\mathcal{GRS}$), which is not necessarily in line with the EU taxonomy. The breakdown of the four green intensity measures is shown in Table 22 and Figure 44. There are clearly two dominant sectors: Utilities and Industrials. Consumer Discretionary is also a significant contributor, while Materials is lagging behind. All these results are consistent with our narrow definition of the satellite portfolio.

Figure 44: Breakdown in % of green intensities (MSCI World, Dec. 2021)



Source: MSCI (2023) & Authors' calculations.

3.2.3 Green infrastructure

The European Commission defines green infrastructure as "*a strategically planned network of natural and semi-natural areas with other environmental features, designed and managed to deliver a wide range of ecosystem services, while also enhancing biodiversity*". Green infrastructure is implemented in a variety of sectors, from the energy sector through energy transmission infrastructure, and the water sector through natural water retention measures or sustainable urban drainage systems, to the urban landscape with street trees to help sequester carbon or green roofs to help regulate the temperature of buildings. The cost of implementing green infrastructure will come from the identification, mapping, planning and creation of the infrastructure, but the environmental, economic and social benefits will make it worthwhile. Funds that assess infrastructure needs are emerging in the marketplace and typically invest in owners of sustainable infrastructure assets as well as companies that are leaders in infrastructure investment. Besides infrastructure funds, investors also consider direct investments such as green parking, water infrastructure, and floodplain levees.

3.2.4 Sustainable real estate

The real estate sector emits significant amounts of CO_2 through building operations, building materials, and construction. Actions need to be taken in the construction of new buildings, but also in the renovation of existing buildings. For existing buildings, it is very important to reduce energy consumption, eliminate emissions from energy and refrigerants, and reduce or eliminate the use of fossil fuels. This is done by improving equipment such as insulation, ventilation, and the use of renewable energy, as well as optimizing operations by installing GHG monitors or adjusting temperature settings. New construction must be energy and carbon efficient, taking into account new and clean technologies. Funds dedicated to sustainable real estate have entered the market, typically targeting multiple sectors and countries with a specific allocation to reach net-zero by 2050. They mostly follow the CRREM (Carbon Risk Real Estate Monitor) path, targeting 1.5°C/2°C using a Paris-aligned decarbonization pathway per country and building type, ranging from office buildings to retail stores and hotels.

4 Tracking error risk of the core/satellite portfolio

Let α be the proportion of the satellite portfolio. Using the previous notations, the return of the core/satellite portfolio is equal to:

$$\begin{aligned} R(x) &= (1-\alpha) \underbrace{\left(\alpha_{\text{Equity}}^{\text{Core}} R\left(x_{\text{Equity}}^{\text{Core}}\right) + \alpha_{\text{Bond}}^{\text{Core}} R\left(x_{\text{Bond}}^{\text{Core}}\right)\right)}_{\text{Core portfolio's return}} + \\ & \quad \alpha \underbrace{\left(\alpha_{\text{Equity}}^{\text{Satellite}} R\left(x_{\text{Equity}}^{\text{Satellite}}\right) + \alpha_{\text{Bond}}^{\text{Satellite}} R\left(x_{\text{Bond}}^{\text{Satellite}}\right)\right)}_{\text{Satellite portfolio's return}} \end{aligned}$$

By construction, we have $\alpha_{\text{Equity}}^{\text{Core}} + \alpha_{\text{Bond}}^{\text{Core}} = 1$ and $\alpha_{\text{Equity}}^{\text{Satellite}} + \alpha_{\text{Bond}}^{\text{Satellite}} = 1$. The proportion invested in equities is equal to $\alpha_{\text{Equity}} = (1-\alpha)\,\alpha_{\text{Equity}}^{\text{Core}} + \alpha\,\alpha_{\text{Equity}}^{\text{Satellite}}$ whereas the proportion invested in bonds is the complementary part ($\alpha_{\text{Bond}} = 1 - \alpha_{\text{Equity}}$). We deduce that:

$$R(x) = \tilde{\boldsymbol{\alpha}}^\top \tilde{\boldsymbol{R}}(x)$$

where $\tilde{\boldsymbol{R}}(x) = \left(R\left(x_{\text{Equity}}^{\text{Core}}\right), R\left(x_{\text{Bond}}^{\text{Core}}\right), R\left(x_{\text{Equity}}^{\text{Satellite}}\right), R\left(x_{\text{Bond}}^{\text{Satellite}}\right)\right)$ and:

$$\tilde{\boldsymbol{\alpha}} = \begin{pmatrix} (1-\alpha)\,\alpha_{\text{Equity}}^{\text{Core}} \\ (1-\alpha)\,\alpha_{\text{Bond}}^{\text{Core}} \\ \alpha\,\alpha_{\text{Equity}}^{\text{Satellite}} \\ \alpha\,\alpha_{\text{Bond}}^{\text{Satellite}} \end{pmatrix}$$

The benchmark portfolio's return is given by:

$$\begin{aligned} R(b) &= \alpha_{\text{Equity}} R\left(b_{\text{Equity}}\right) + \left(1-\alpha_{\text{Equity}}\right) R\left(b_{\text{Bond}}\right) \\ &= \left((1-\alpha)\,\alpha_{\text{Equity}}^{\text{Core}} + \alpha\,\alpha_{\text{Equity}}^{\text{Satellite}}\right) R\left(b_{\text{Equity}}\right) + \\ &\quad \left(1-(1-\alpha)\,\alpha_{\text{Equity}}^{\text{Core}} - \alpha\,\alpha_{\text{Equity}}^{\text{Satellite}}\right) R\left(b_{\text{Bond}}\right) \end{aligned}$$

We notice that:

$$\begin{aligned} \left(1-(1-\alpha)\,\alpha_{\text{Equity}}^{\text{Core}} - \alpha\,\alpha_{\text{Equity}}^{\text{Satellite}}\right) &= \left(1-\alpha+\alpha-(1-\alpha)\,\alpha_{\text{Equity}}^{\text{Core}} - \alpha\,\alpha_{\text{Equity}}^{\text{Satellite}}\right) \\ &= (1-\alpha)\left(1-\alpha_{\text{Equity}}^{\text{Core}}\right) + \alpha\left(1-\alpha_{\text{Equity}}^{\text{Satellite}}\right) \\ &= (1-\alpha)\,\alpha_{\text{Bond}}^{\text{Core}} + \alpha\,\alpha_{\text{Bond}}^{\text{Satellite}} \end{aligned}$$

It follows that:

$$\begin{aligned} R(b) &= \left((1-\alpha)\,\alpha_{\text{Equity}}^{\text{Core}} + \alpha\,\alpha_{\text{Equity}}^{\text{Satellite}}\right) R\left(b_{\text{Equity}}\right) + \\ &\quad \left((1-\alpha)\,\alpha_{\text{Bond}}^{\text{Core}} + \alpha\,\alpha_{\text{Bond}}^{\text{Satellite}}\right) R\left(b_{\text{Bond}}\right) \\ &= (1-\alpha)\,\alpha_{\text{Equity}}^{\text{Core}} R\left(b_{\text{Equity}}\right) + (1-\alpha)\,\alpha_{\text{Bond}}^{\text{Core}} R\left(b_{\text{Bond}}\right) + \\ &\quad \alpha\,\alpha_{\text{Equity}}^{\text{Satellite}} R\left(b_{\text{Equity}}\right) + \alpha\,\alpha_{\text{Bond}}^{\text{Satellite}} R\left(b_{\text{Bond}}\right) \end{aligned}$$

We deduce that:

$$R(b) = \tilde{\boldsymbol{\alpha}}^\top \tilde{\boldsymbol{R}}(b)$$

where $\tilde{\boldsymbol{R}}(b) = \left(R\left(b_{\text{Equity}}\right), R\left(b_{\text{Bond}}\right), R\left(b_{\text{Equity}}\right), R\left(b_{\text{Bond}}\right)\right)$. The tracking error is defined as:

$$\begin{aligned} e &= R(x) - R(b) \\ &= \tilde{\boldsymbol{\alpha}}^\top \left(\tilde{\boldsymbol{R}}(x) - \tilde{\boldsymbol{R}}(b)\right) \end{aligned}$$

Let $\tilde{\boldsymbol{\Sigma}}\left(x \mid b\right)$ be the 4×4 covariance matrix of $\tilde{\boldsymbol{R}}(x) - \tilde{\boldsymbol{R}}(b)$. We conclude that the tracking error volatility of the core/satellite portfolio has the following expression:

$$\begin{aligned} \sigma\left(x \mid b\right) &= \sqrt{\tilde{\boldsymbol{\alpha}}^\top \tilde{\boldsymbol{\Sigma}}\left(x \mid b\right) \tilde{\boldsymbol{\alpha}}} \\ &= \sqrt{\left(\tilde{\boldsymbol{\alpha}} \odot \tilde{\boldsymbol{\sigma}}\left(x \mid b\right)\right)^\top \tilde{\boldsymbol{\rho}}\left(x \mid b\right) \left(\tilde{\boldsymbol{\alpha}} \odot \tilde{\boldsymbol{\sigma}}\left(x \mid b\right)\right)} \end{aligned}$$

where $\tilde{\boldsymbol{\rho}}\left(x \mid b\right)$ is the correlation matrix of $R(x) - R(b)$ and $\tilde{\boldsymbol{\sigma}}\left(x \mid b\right)$ is the vector of tracking error volatilities:

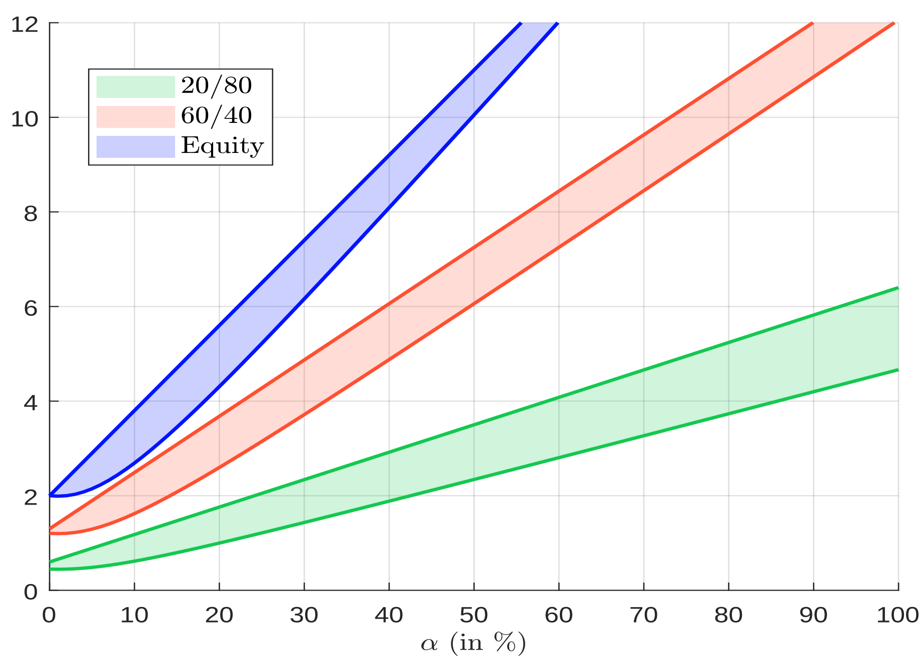
$$\tilde{\boldsymbol{\sigma}}\left(x \mid b\right) = \begin{pmatrix} \sigma\left(x_{\text{Equity}}^{\text{Core}} \mid b_{\text{Equity}}\right) \\ \sigma\left(x_{\text{Bond}}^{\text{Core}} \mid b_{\text{Bond}}\right) \\ \sigma\left(x_{\text{Equity}}^{\text{Satellite}} \mid b_{\text{Equity}}\right) \\ \sigma\left(x_{\text{Bond}}^{\text{Satellite}} \mid b_{\text{Bond}}\right) \end{pmatrix}$$

Suppose the tracking error volatilities are 2% for the core equity portfolio, 25 bps for the core bond portfolio, 20% for the satellite equity portfolio, and 3% for the satellite bond portfolio. We consider several constant mix strategies with the same allocation within the core and satellite portfolios. We then compute the lower and upper bounds of the tracking error volatility of the core/satellite portfolio. For the lower bound, we set all correlations to zero. For the upper bound, we assume an 80% correlation between the two equity baskets, an 80% correlation between the two bond baskets, and a 0% correlation between the equity and bond baskets. The results are shown in Table 23 for three different values of α. When the satellite weight is set to 20%, the tracking error volatility is between 63 and 80 bps for the pure bond allocation. For the 60/40 constant mix allocation, we obtain $\sigma\left(x \mid b\right) \in \left[2.60\%, 3.68\%\right]$, while for the pure equity allocation we have $\sigma\left(x \mid b\right) \in \left[4.31\%, 5.60\%\right]$. Figure **??** shows the evolution of the lower and upper bounds of the tracking error volatility as the allocation in the satellite increases.

Table 23: Estimation of the tracking error volatility of the core/satellite portfolio (in %)

	α	Bond	Defensive	Balanced	60/40	Dynamic	Equity
	10%	0.38	0.62	1.36	1.62	2.15	2.69
Lower bound	20%	0.63	1.00	2.18	2.60	3.45	4.31
	30%	0.92	1.43	3.11	3.71	4.93	6.16
	10%	0.53	1.18	2.16	2.49	3.15	3.80
Upper bound	20%	0.80	1.76	3.20	3.68	4.64	5.60
	30%	1.07	2.34	4.24	4.87	6.13	7.40

Figure 45: Lower and upper bound of the tracking error volatility (in %)



5 Conclusion

This article is part of a larger work on net-zero investments, following the implementation of the integrated approach by Barahhou *et al.* (2022), where the decarbonization and transition dimensions are addressed simultaneously. In this approach, we observed an increase in tracking error risk, as we found that carbon intensity and green intensity may currently be positively correlated. This is particularly true for equity markets, but less so for bond markets. The core satellite approach explored here presents itself as a solution to assess both decarbonization and transition dimensions, but in a separate way, i.e. carbon intensity and green intensity are managed separately. Therefore, we assume that the core portfolio addresses the decarbonization dimension, while the satellite portfolio addresses the transition dimension.

The management of the core portfolio incorporates several elements of the integrated approach. The first element is, of course, the specification of the decarbonization pathway. As in the previous study, we reiterate that its choice has a major impact on portfolio construction. The choice of an aggressive decarbonization path may entail a high diversification risk, as the investment universe may be drastically shrunk. This is particularly true if the net-zero investment policy takes into account the investor's global allocation. We also face a gap risk if we aggressively decarbonize financial portfolios while the economy fails to decarbonize. Of course, financial markets need to decarbonize faster than the economy, but if the gap is too large and the pace is too high, there is a risk that the investment universe will shrink too much, reducing the diversification and liquidity of the portfolio. The second element is the self-decarbonization of the core portfolio. In this study, we use carbon momentum to measure the ability of the core portfolio to self-decarbonize, but other metrics can be used. Temperature scores are generally more sophisticated than carbon momentum because the latter only considers the participation dimension, not the ambition and contribution factors of the $\mathcal{PAC}$ framework (Le Guenedal *et al.*, 2022). However, carbon momentum has the advantage of being easy to calculate because it takes into account companies' past efforts. The goal of self-decarbonization is to make the decarbonization path of the portfolio endogenous, as the dynamics of the path cannot be explained by the rebalancing process alone. The third element is the definition of carbon intensity. Are we using Scope 1 and 2 emissions, or are we including Scope 3 emissions? In general, a net zero investment policy needs to include both direct and indirect emissions, because we can't decarbonize one part of the system and leave the other part in place. The problem is that Scope 3 emissions are not well measured. The data is very noisy and there are many data gaps. For example, upstream Scope 3 emissions are generally estimated using Leontief analysis and are highly dependent on the input-output table. Therefore, the choice of scope remains an open question today. In addition to these three elements, we are introducing a new concept that is essential to net zero. In fact, as the International Energy Agency has explained, there is a sequence to achieving a low-carbon economy by 2050. First, we need to decarbonize electricity, mainly by 2035, while the last sector to decarbonize will be industry (IEA, 2021). Therefore, it is important to consider the sequencing applied to sectoral decarbonization, in particular the need to decarbonize the power sector first. As KPMG (2023, page 30) said, "*if the power generation is carbonated, it is difficult or impossible to achieve carbon neutrality in other sectors.*" This net-zero characteristic has important implications for portfolio construction. Indeed, we know that a decarbonization process is a strategy that overweights financials and underweights energy, materials, and utilities. But the sequencing characteristic requires that utilities be the key element of a net-zero investment policy. Therefore, we propose that the utilities sector follow its specific NZE scenario rather than the global NZE scenario[13].

[13]We could use more sectoral decarbonization pathways, but a comprehensive approach may be too con-

The results of the core portfolio are strongly influenced by the various factors listed above, which can be implemented through constraints applied to the optimization problem. Taking into account upstream Scope 3 emissions will significantly increase the tracking error, while the chosen decarbonization path will also affect the tracking error of the portfolio. Taking into account the self-decarbonization aspect through the different carbon momentum constraints also contributes to an increase in tracking error volatility, this time not only for Scope 3 emissions, but also for Scopes 1 and 2. More surprisingly, the inclusion of the NZE scenario for the electricity sector does not have a significant impact on the tracking error volatility, supporting a limited increase. This is due to a new arbitrage between the utilities sector and the other carbon-intensive sectors such as energy, industrials and materials. These results for the core equity portfolio remain the same for the core bond portfolio when we measure active risk using active share and duration-times-spread deviation. However, as we reported in the first part of this study, the core bond portfolio is easier to manage than the core equity portfolio when we focus on tracking risk and diversification loss. For example, in the short term, we expect a tracking error volatility of 2% for the core equity portfolio and 25 bps for the core bond portfolio for a net-zero implementation with a reasonable decarbonization path, such as the average NZAOA trajectory.

Through the satellite portfolio, we address the transition dimension and provide a comprehensible approach to the financing needs and the investment universe to be considered. The $3.5 trillion of investment needed is concentrated in three sectors: power, buildings, and transportation. Not all sectors are created equal when it comes to achieving a net-zero economy by 2050, as these three sectors account for more than 90% of the financing needs. In fact, one sector dominates all others: electricity. This includes power generation, but also power grids and storage. For example, we need to build three times as many electricity grids and multiply electricity generation by a factor of 3. This is a huge challenge for the utilities sector (IEA, 2022b, Chapter 6). In addition, green power requires the production of materials and critical minerals, which puts a lot of pressure on the supply side as natural resources are limited. Ultimately, the utilities sector is the strong nexus of the future low-carbon global value chain. If we include buildings and mobility, the financing needs are concentrated in just a few sectors. This has important implications for investors. Indeed, the investment universe of the satellite portfolio is very different from that of the core portfolio. In other words, a net-zero funding portfolio has strong sector bias compared to traditional financial benchmarks such as the MSCI World Index or the Bloomberg Global Aggregate Index. From this perspective, we propose a narrow definition of the satellite investment portfolio. Looking at the GICS classification, we find that five sectors are excluded at Level 1. In fact, we identify only 29 sub-industries out of the 163 included in Level 4 of the GICS classification.

Green bonds are the inevitable securities of the satellite portfolio. Current issuance is about $500 billion ± $50 billion, depending on the definition of the perimeter and the certification process. This represents 15% of total net zero financing needs. We are far from a situation where the net zero scenario is fully financed. Therefore, we can include other instruments such as sustainability, sustainability linked and transition bonds. However, the selection of these securities requires in-depth due diligence in order to select the right use of proceeds. This is the main feature of the satellite portfolio. By construction, it can only be a bottom-up approach, where each security is analyzed to fit the net-zero requirements. On average, we expect the satellite bond portfolio to have a tracking error of around 3% relative to a traditional global aggregate benchmark. Green stocks, on the other hand, through the various thematic funds and asset picking processes, will give more freedom in choosing what to finance for the transition. The recent development of thematic equity funds focused on

straining for portfolio construction.

net zero transition can help build the satellite equity portfolio, but the fund manager can also develop his own stock picking process. The choice of the green intensity measure is then an important part of the selection process. Using the EU taxonomy has the advantage of being an implicit certification-like process. This can be an alternative to our narrow definition for specifying the investment universe of the satellite equity portfolio, even if the universes are very closed. Nevertheless, we find that the green intensity metric has a significant impact. For example, industrials are more represented when we focus on green revenues rather than green capex. On average, we expect the satellite equity portfolio to have a tracking error of around 20% relative to the MSCI World index. Finally, investments in sustainable infrastructure and real estate can complete the satellite portfolio.

The allocation between the core and satellite portfolios depends on several factors. First, it depends on the investment opportunities for the satellite portfolio. Today, we see a large imbalance between the supply of green assets and what is needed to finance the transition. Therefore, we can expect the allocation in the satellite portfolio to be small, but to increase in the future. Second, the allocation depends on the utility function. What level of greenness is acceptable and compatible with the allocation policy and green preferences of the end investors? Therefore, for the same investors, the allocation in the satellite will differ depending on whether it is their strategic asset allocation, a multi-asset fund, an equity fund or a bond fund. Furthermore, the utility function may also depend on carbon intensity, not just green intensity. We prefer that the two metrics are negatively correlated, which is the best situation for building a core-satellite portfolio because reducing carbon intensity is equivalent to increasing green intensity. Unfortunately, this is not what we observe today, and the two metrics are positively correlated. If we assume that 20% is a baseline for the satellite allocation, the tracking error volatility of the core-satellite portfolio is around 3% for a 60/40 constant mix portfolio.

Beyond the construction of the core-satellite portfolio, this study raises two questions about the net-zero emissions scenario and its implications. The first question is who will finance the transition? According to NGFS (2022), the net-zero scenario implies an increase in public investment and a decrease in private investment compared to the baseline scenario. These results may be disturbing. The narrative is as follows. Private investors may be frightened by the huge investment needs of the utility sector and expect a sharp decline in the sector's return on equity. At the same time, public investment must increase to finance the transition. This puts pressure on interest rates and increases public debt. Private investors may then prefer to buy high-yield government bonds rather than invest directly in utilities. This is what we observe when we apply the Black-Litterman model to decarbonized portfolios and calculate the implied risk premia priced in by investors. The second question is the place of commodity markets in a net-zero economy, and then the place of commodities in a net-zero investment policy. This is a difficult question to answer because the net-zero transition implies a large increase in the supply of materials and critical minerals. Clean energy technologies rely on traditional metals (aluminium, copper, steel, and zinc) and rare elements such as lithium or neodymium. The mining or production of these materials may be concentrated in a few countries. For example, the top producers of lithium are Australia, Chile, China, and Argentina, which account for more than 90% of global lithium production. The second question then relates to geopolitical issues, but also to biodiversity issues. In conclusion, this study shows that net-zero investing is a multi-faceted investment problem, but a core-satellite approach can help to simplify the implementation.

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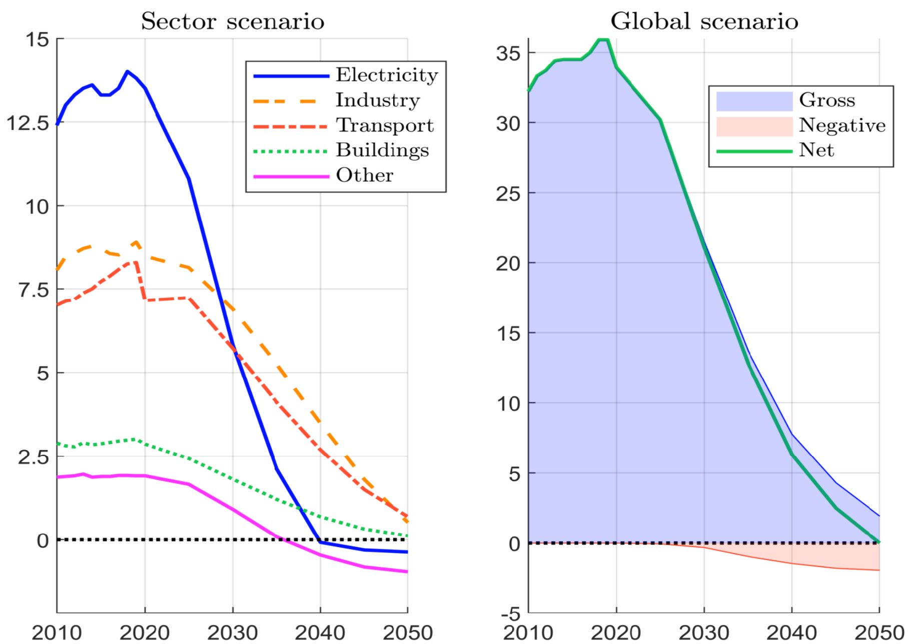
A Additional results

A.1 Figures

Figure 46: CO_2 emissions by sector in the IEA NZE scenario (in $GtCO_2e$)



Source: IEA (2021); Barahhou *et al.* (2022).

A.2 Tables

Table 24: Intermediate targets of NZAOA members

Asset owner	Sub-portfolio target
BT Pension Scheme	Reduce scope 1 and 2 carbon intensity of its equity and credit portfolio by at least 25% and real estate by at least 33% by 2025
CDPQ	Reduce portfolio carbon intensity by 60% by 2030
CNP	Reduce the carbon footprint of its directly held equity and corporate bond portfolio by a further 25% by 2025, and by 10% for its directly held real estate portfolio (base year: 2019)
Crédit Agricole Assurances	Reduce the carbon footprint of listed equity and corporate bond investment portfolio by 25% by 2025
ERAFP	Reducing carbon intensity by 25% between 2019 and 2024 for scopes 1 and 2 of listed equity and corporate bond portfolios. Aligning non-residential real estate portfolio with a 1.5°C target scenario
FRR	Reduce the absolute portfolio carbon emissions by 20% by 2025
Generali Group	Reduce portfolio carbon intensity by 25% by 2025
HUK-COBURG	Reduce the CO2 emissions of the listed equities and corporate bonds investment portfolio by 22% by 2025 (base year: 2019). Coverage of investments in infrastructure and real estate will be added gradually
M&G plc	By 2030, reduce carbon emissions intensity in public equity and public corporate debt portfolios by 50% and by 36% in real-estate (base year: 2019)
Meiji Yasuda Life	Reduce carbon intensity (scope 1 and 2) from domestic and foreign listed companies as well as real estate by at least 49% by 2030 (base year: fiscal year ending March 31, 2020)
Novartis Pension Fund Switzerland	Reduce greenhouse gas emissions of equity, corporate bond, and real estate investments by 50% by 2030 (base year: 2019)
Swiss Re	Reduce carbon intensity of the corporate bond and listed equity portfolio by 35% by 2025 (base year: 2018)
UNIQA	Reduce scope 1 and 2 carbon emission intensity for listed equity, corporate bond, and real estate portfolio by 15% by 2025 (base year: 2021)
University of Toronto AM Corporation	Reduce the carbon footprint of long-term portfolios by 40% by 2030
VidaCaixa S.A.U.	Reduce carbon emission intensity (scopes 1 and 2) of corporate investments by at least 50% by 2030 (base year: 2019)
Wespath	Reduce the carbon intensity of all investment funds by 35% by 2025 (base year: 2018)

Source: NZAOA, July 2023, https://www.unepfi.org/net-zero-alliance/resources/member-targets.