Chapter 1

Portfolio Alignment and Net Zero Investing

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1.1 Introduction

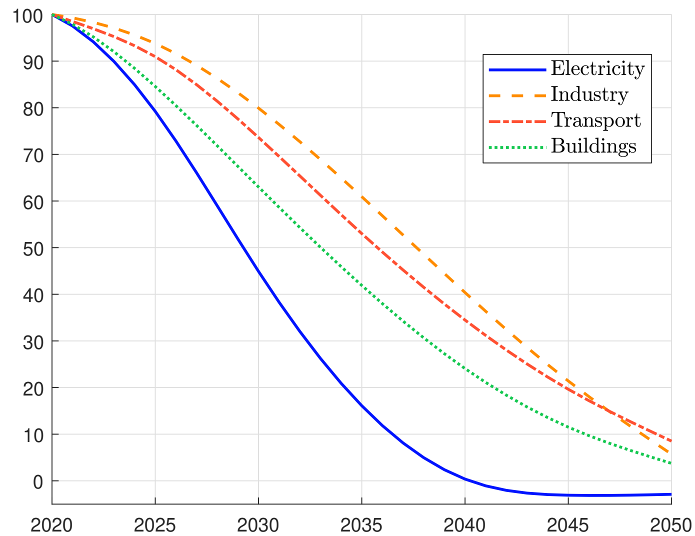
The concept of portfolio alignment emerged at the end of the 2010s with the European Commission's willingness to create climate benchmarks linked to the goals of the Paris Agreement. The development of the CTB and PAB benchmarks[1] is then an important step that has popularized the practice of portfolio alignment [17]. The two benchmarks use a pre-defined decarbonization pathway based on the IPCC recommendation to limit the temperature anomaly to below 2°C. They also incorporate other constraints aimed at financing the transition to a low-carbon economy. In a sense, they combine two well-established climate investment strategies: portfolio decarbonization and climate solutions. Portfolio decarbonization is the process of reducing the

[1] Although they are not labels, we also use the abusive terms CTB and PAB labels.

carbon footprint of an investment portfolio relative to a benchmark portfolio [2]. It involves shifting investments from higher carbon emitting assets to lower carbon emitting assets. Climate solutions are thematic investments and strategies that directly contribute to mitigating climate change and adapting to its impacts. These solutions focus on financing technologies, projects and practices that promote the green economy, such as investments in solar, wind and hydro power, carbon capture solutions, sustainable infrastructure or green real estate. To include climate solutions, the TEG proposed two constraints: a minimum exposure to sectors highly exposed to climate change and a minimum share of green revenues (or capex) in line with the EU taxonomy. Unfortunately, in the final version of the CTB and PAB benchmarks, the reference to green footprint (*e.g.*, green revenues or capex) disappear [16]. In addition, the final version of the climate impact sectors includes a large number of industries, making this criterion irrelevant for the inclusion of climate solutions [12].

The second factor in the development of portfolio alignment is the publication of the net-zero scenario by the International Energy Agency in May 2021 [1]. Until the IEA report, most of the decarbonization pathways are exogenous. With the publication of the IEA report, the decarbonization pathway of the net-zero scenario is the result of in-depth sector analysis. For each sector, the IEA creates a decarbonization scenario that takes into account the development of energy efficiency, the implementation of decarbonization tools and techniques, behavioral changes, and other factors, including the deployment of carbon capture and storage and massive investments to finance the transition to a low-carbon economy. The release of the IEA report gives hope that it is possible to achieve net zero by 2050 because it is a credible roadmap to follow and not just a hypothetical scenario. Investors and the financial community will study this net-zero scenario closely and adopt it as their own. So it's no coincidence that 2021 will see a proliferation of net zero initiatives in the financial sector, culminating in the launch of the Glasgow Financial Alliance for Net Zero (GFANZ). During COP26 in Glasgow in November 2021, the GFANZ Chair announced that more than 450 financial companies (banks, asset managers, asset owners, insurance companies, etc.) from 45 countries, representing more than $130 trillion in assets under management, are committed to tackling climate change. While the PAB/CTB decarbonization pathways are global, the IEA scenario emphasizes that decarbonization efforts must be differentiated. Not all sectors are the same. Indeed, electricity must be decarbonized as a priority, as shown in Figure 1.1. By 2035, this sector must achieve a decarbonization rate of 85% if we are to reach net zero by 2050. Any delay in the decarbonization of the electricity sector will jeopardize the net zero goal, because the decarbonization of the other sectors depends on this first intermediate step. Figure 1.1 also shows that there is a sequence of decarbonization and a sequence of transition. While electricity must be the first sector to decarbonize, industrials is the last sector to decarbonize because it needs green electricity, green materials, green buildings, and green transportation. The IEA report was not written specifically for financial institutions, but rather for policymakers and carbon-intensive industries. However, the report has had a resounding impact on the financial industry by showing what a net zero economy would look like. We note that the report talks more about investment and financing than about decarbonization, with the following frequency: 220 occurrences for investment, 42 references for financing, and only 35 times for decarbonization[2].

FIGURE 1.1: Sectoral decarbonization pathways



Source: [1, Figure 3.1, page 100] & Author's calculations.

Strictly speaking, portfolio alignment means that the carbon emissions trajectory of the portfolio is aligned or follows a decarbonization path of a given climate scenario. However, the IEA's net-zero scenario shows that decarbonization is not exogenous. So what does it mean for investors to align their portfolios with a net-zero scenario? Over the past decade, we have seen a shift among investors to view portfolio alignment not only as a portfolio construction exercise with a carbon footprint constraint, but also as an investment exercise that contributes to achieving net zero by 2050. In this approach, portfolio alignment is not a rebalancing process to reduce the carbon footprint, but rather a selection of investments to increase the greenness of the economy. The differences between carbon footprint and green footprint are at the heart of the concept of portfolio alignment and explain why it differs from portfolio decarbonization.

[2]We count the word and its derivatives. For example, the 35 occurrences of decarbonization are broken down as follows: decarbonisation (13 occurrences), decarbonised (8 occurrences), decarbonise (7 occurrences), and decarbonising (7 occurrences).

1.2 Portfolio decarbonization vs. portfolio alignment

As explained by [3] and [5], portfolio alignment is not portfolio decarbonization. However, many investors continue to confuse the two concepts [21]. There are several reasons for this confusion. First, portfolio alignment involves decarbonizing the portfolio, which implies that alignment is related to decarbonization. Second, while portfolio decarbonization is well defined, this is not the case for portfolio alignment, which is a fuzzy term. It is a common term in the financial industry, but there is no accepted definition among investors. We know that portfolio alignment goes beyond portfolio decarbonization, but like many terms in sustainable finance, the concept can vary across countries and investor types. For example, portfolio alignment may or may not include a social pillar, leading to the concept of just transition. Third, portfolio alignment is closely related to net zero. When investors talk about portfolio alignment today, they implicitly assume that their investments are aligned with a net-zero scenario. The difficulty is that a climate scenario has a low probability of being realized and is, by definition, the path of a stochastic system. This means that there are many net-zero scenarios that change every time we have new information about the climate system.

CTB and PAB decarbonization pathways

CTB (Climate Transition Benchmark) and PAB (Paris-Aligned Benchmark) are two types of climate benchmarks introduced by the European Union (EU) to assess the alignment of investment portfolios with climate goals. The CTB and PAB decrabonization pathways are defined as:

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

where t_0 is the baseline date, $\Delta\boldsymbol{\mathcal{R}} = 7\%$ and $\boldsymbol{\mathcal{R}}^-$ takes the values 30% (CTB) and 50% (PAB) respectively. Below we report the reduction rate in % of CTB and PAB labels when the base year is 2020:

Year	2020	2025	2030	2035	2040	2045	2050
CTB	30.0	51.3	66.1	76.4	83.6	88.6	92.1
PAB	50.0	65.2	75.8	83.2	88.3	91.9	94.3

For example, in 2025, this implies a reduction of 51.3% and 65.2% from the 2020 carbon intensity of the benchmark for the CTB and PAB labels, respectively. The CTB decarbonization pathway is less aggressive. In fact, the CTB pathway follows the PAB pathway with a lag of 4.6 years [12].

1.2.1 The various dimensions of net zero

Defining a net-zero investment portfolio is not easy because it has several dimensions. First, a net-zero portfolio is not a low-carbon portfolio, because when we build a low-carbon portfolio, the goal is very simple. We want to reduce the carbon footprint of a given portfolio. So a low-carbon portfolio is a static approach to decarbonization. A net-zero portfolio is a dynamic approach to decarbonization to get to net zero by 2050. So the concept of self-decarbonization is important. And we can't look at a net-zero portfolio as an investment process where we just apply a sequence of decarbonization rates and a sequence of portfolio rebalancing. In fact, some of the decarbonization has to be endogenous. Another important difference is that a net-zero portfolio has to take into account the financing of the transition. Thus, the greenness or green intensity of the portfolio is also an important component of a net zero policy. This dimension is sometimes called the contribution part and is related to the concept of climate solutions. A net zero investment policy therefore has at least two main dimensions: portfolio decarbonization and financing the transition. Net zero investing is not just a carbon footprint issue, it is also a green footprint issue, and these two concepts are different.

1.2.2 The issue of portfolio rebalancing and the concept of self-decarbonization

To illustrate the concept of self-decarbonization, we assume that the decarbonization rate at the beginning of the year is 30%. At the end of the year, we want to have a decarbonization rate of 35% relative to the benchmark. We look at two extreme cases. At the end of the year, the decarbonization rate of the portfolio is 25%, which means that the carbon footprint of our portfolio has increased during the year. In this case, we have to rebalance the portfolio to get to the 35% level. This is the bad case because the self-decarbonization of the portfolio is zero. In the second case, we assume that at the end of the year, the decarbonization rate of the portfolio is greater than 35%, which means that we do not need to rebalance the portfolio. This is the good case because we do not have to rebalance the portfolio. So we can always follow a decarbonization path by rebalancing a portfolio of liquid assets, but it does not mean that the investment process is a net zero investment policy. In particular, there are some financial businesses where it is difficult to rebalance the portfolio because the assets are not liquid, for example banking and credit or insurance.

How to implement self-decarbonization in portfolio alignment? We recall that the carbon intensity at time $t+1$ is related to the carbon intensity at time t by the following equation[3]:

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

[3] The rebalancing dates are assumed to be synchronized at times t, $t+1$, and so on.

where $\boldsymbol{\mathcal{R}}(t,t+1)$ is the carbon reduction between t and $t+1$. This equation is valid at time $t+1$ once we know the value of carbon intensity at time $t+1$. We can decompose the carbon reduction into a predictable component and an unpredictable component:

$$\boldsymbol{\mathcal{R}}(t,t+1) = \mathbb{E}\left[\boldsymbol{\mathcal{R}}(t,t+1) \mid \mathcal{F}_t\right] + \varepsilon(t+1)$$

where $\mathcal{F}_t$ is the filtration at time t and $\varepsilon(t+1)$ is a stochastic noise process. In this case, $\boldsymbol{\mathcal{R}}(t,t+1)$ is random and we have[4]:

$$\mathbb{E}\left[\boldsymbol{\mathcal{CI}}(t+1) \mid \mathcal{F}_t\right] = \left(1 - \mathbb{E}\left[\boldsymbol{\mathcal{R}}(t,t+1) \mid \mathcal{F}_t\right]\right)\boldsymbol{\mathcal{CI}}(t)$$

Implementing self-decarbonization requires defining a process to control the expected carbon reduction $\mathbb{E}\left[\boldsymbol{\mathcal{R}}(t,t+1) \mid \mathcal{F}_t\right]$. Two main approaches are used by professionals. The first is to predict the carbon reduction $\boldsymbol{\mathcal{R}}(t,t+1)$ using time series modeling of discrete processes. Since the number of observations is relatively small, we can only use simple econometric models such as the linear (or log-linear) trend model. The second is to incorporate forward-looking measures of the future carbon path. This is typically done using the targets announced by issuers. In this case, investors use implied temperature ratings and map these ratings to expected carbon reductions.

Carbon momentum

[11] define the carbon trend by considering the linear trend model:

$$\boldsymbol{\mathcal{CE}}(t) = \beta_0 + \beta_1(t - t_0) + u(t) \tag{1.1}$$

where $\boldsymbol{\mathcal{CE}}(t)$ is the carbon emissions and $u(t) \sim \mathcal{N}\left(0, \sigma_u^2\right)$. An alternative model is the log-linear trend model proposed by [21]:

$$\ln \boldsymbol{\mathcal{CE}}(t) = \gamma_0 + \gamma_1(t - t_0) + v(t) \tag{1.2}$$

where $v(t) \sim \mathcal{N}\left(0, \sigma_v^2\right)$. The parameters β_0, β_1, γ_0 and γ_1 are estimated with the least squares method and a sample of observations. [11] define the carbon momentum as the historical growth rate of carbon emissions. In the case of the linear trend model, we have $\boldsymbol{\mathcal{CM}}(t) = \dfrac{\hat{\beta}_1}{\boldsymbol{\mathcal{CE}}(t)}$ while it is directly equal to $\hat{\gamma}_1$ in the case of the log-linear trend model. For example, $\boldsymbol{\mathcal{CM}}(t) = -5\%$ means that the issuer has reduced his carbon emissions by 5% per year. The carbon momentum can also be estimated using the carbon intensity instead of the carbon emissions.

[4]We assume that $\mathbb{E}\left[\varepsilon(t+1)\right] = 0$.

1.2.3 Carbon intensity and green intensity

Reducing the carbon footprint of a portfolio is not equivalent to increasing the green footprint of the portfolio or improving the greenness of the economy. The two goals are only equivalent if the correlation between the carbon intensity and the green intensity of issuers is -100%. This is currently not the case. For example, Table 1.1 shows the carbon and green[5] intensities of sectors in the MSCI EMU Index at the end of June 2024. We find that high carbon sectors also have high green intensities. On average, utilities stocks in the MSCI EMU stocks have a Scope 1 of 433 tonnes of CO_2 per million dollars of revenue, while the green turnover, capex and opex are 31.6%, 75.4% and 55.7%, respectively. Table 1.2 gives the sector breakdown in % of the carbon and green intensities. The utilities sector represents 5.4% of the weight in the MSCI EMU index, but it contributes 35.5% of the scope 1 emissions and 44% of the green capex of the MSCI EMU index. Three sectors account for about 80% of the greenness of the MSCI EMU index: consumer discretionary, industrials and utilities. However, two of these sectors are among the largest contributors to the carbon footprint (industrials and utilities). So when we reduce the carbon footprint of a portfolio, we run the risk of reducing the green footprint of the portfolio and the economy.

Green intensity

Like carbon intensity, which is a relative measure of carbon footprint, green intensity is a relative measure of green footprint (or greenness). However, the two measures are conceptually different. In fact, carbon intensity is the ratio of an issuer's carbon emissions to its financial size, such as EVIC or revenue. Carbon intensity is then expressed in $tCO_2e/\$$ mn. In contrast, green intensity measures the proportion of the issuer's operations that are considered green. Green intensity is therefore expressed as a percentage. For example, the most common measure is based on revenue (or turnover) and is also called green revenue share:

$$\boldsymbol{\mathcal{GI}} = \frac{\mathcal{GR}}{\mathcal{TR}}$$

where $\mathcal{GR}$ is the green revenue and $\mathcal{TR}$ is the total revenue of the issuer. Another approach to calculating green intensity is to use green capex. While the green revenue ratio measures the current green footprint of a company, the green capex ratio measures the future green footprint of a company because the future greenness of a company is related to the current investment and R&D in green activities.

[5] We use the three measures of green intensity defined in the EU taxonomy: green turnover, green capex (capital expenditure) and green opex (operating expenditure). The data correspond to the figures reported by the companies.

TABLE 1.1: Carbon intensity and green intensity by sector (MSCI EMU, June 2024)

Sector	Weight	Carbon intensity				Green intensity		
		$\mathcal{SC}_1$	$\mathcal{SC}_{1-2}$	$\mathcal{SC}_{1-3}^{\text{up}}$	$\mathcal{SC}_{1-3}$	Turnover	Capex	Opex
	(in %)	(in tCO_2e/$ mn)				(in %)		
Communication Services	4.3	2.6	32.2	73.6	133.4	1.1	0.5	0.2
Consumer Discretionary	14.7	6.7	19.5	170.9	617.7	2.0	7.9	7.4
Consumer Staples	7.1	19.4	34.3	296.0	471.2	0.0	7.9	4.2
Energy	4.1	220.7	237.8	462.5	2 120.9	3.9	19.1	8.7
Financials	19.1	1.2	4.7	25.8	684.5	0.1	0.1	0.1
Health Care	6.9	11.9	28.1	106.5	128.9	0.0	1.1	0.0
Industrials	17.1	20.7	30.7	147.3	3 383.6	9.1	10.7	12.1
Information Technology	15.1	3.6	14.8	106.5	653.2	0.3	0.4	0.3
Materials	5.3	477.4	780.9	1 026.4	1 418.3	1.7	5.5	3.1
Real Estate	1.0	48.1	90.7	119.3	515.0	17.5	35.0	17.2
Utilities	5.4	433.3	497.7	601.0	911.8	31.6	75.4	55.7
MSCI EMU	100.0	65.6	95.5	209.3	1 162.5	4.1	9.2	7.2

Source: MSCI, Trucost & Author's calculations.

TABLE 1.2: Sector breakdown in % of the carbon intensity and taxonomy-aligned green intensity (MSCI EMU, June 2024)

Sector	Weight	Carbon intensity				Green intensity		
		$\mathcal{SC}_1$	$\mathcal{SC}_{1-2}$	$\mathcal{SC}_{1-3}^{\text{up}}$	$\mathcal{SC}_{1-3}$	Turnover	Capex	Opex
Communication Services	4.3	0.2	1.4	1.5	0.5	1.1	0.2	0.1
Consumer Discretionary	14.7	1.5	3.0	12.0	7.8	7.1	12.6	15.1
Consumer Staples	7.1	2.1	2.5	10.0	2.9	0.0	6.1	4.1
Energy	4.1	13.8	10.2	9.1	7.5	3.9	8.5	5.0
Financials	19.1	0.3	0.9	2.4	11.3	0.4	0.3	0.2
Health Care	6.9	1.3	2.0	3.5	0.8	0.0	0.9	0.0
Industrials	17.1	5.4	5.5	12.0	49.7	38.2	19.9	28.7
Information Technology	15.1	0.8	2.3	7.7	8.5	1.1	0.7	0.7
Materials	5.3	38.4	43.1	25.9	6.4	2.2	3.2	2.3
Real Estate	1.0	0.7	0.9	0.6	0.4	4.2	3.7	2.3
Utilities	5.4	35.5	28.0	15.4	4.2	41.8	44.0	41.7

Source: MSCI, Trucost & Author's calculations.

1.3 The portfolio optimization approach

Let w be a portfolio. The general optimization problem is to minimize a financial risk measure $\mathcal{R}(w)$ subject to a set of constraints Ω that take into account climate risk, portfolio alignment and portfolio construction:

$$w^{\star}(t) = \arg\min \mathcal{R}(w) \quad \text{s.t.} \quad w \in \Omega \tag{1.3}$$

A typical portfolio alignment constraint is the decarbonization pathway:

$$\boldsymbol{\mathcal{CI}}(t,w) \leq (1 - \boldsymbol{\mathcal{R}}(t_0,t))\,\boldsymbol{\mathcal{CI}}(t_0, b(t_0)) \tag{1.4}$$

where t_0 is the baseline date, $b(t_0)$ is the benchmark at time t_0 and $\boldsymbol{\mathcal{R}}(t_0,t)$ is the targeted rate of carbon intensity reduction between t_0 and t. Of course, the set Ω can include many other constraints that manage the exclusions or the green footprint. In fact, there is not one specification, but many, depending on the sustainable preferences of the investor. In contrast, the measure of financial risk is relatively standard. In most cases, it is the tracking error variance for equity portfolios and active risk for bond portfolios. This means that the portfolio is optimized relative to a benchmark, which may be a passive benchmark or an active portfolio.

1.3.1 Equity portfolios

For example, [3] use the following optimization problem:

$$\begin{aligned} w^{\star}(t) &= \arg\min \frac{1}{2}(w - b(t))^{\top}\Sigma(t)(w - b(t)) \\ \text{s.t.} & \left\{ \begin{array}{ll} \boldsymbol{\mathcal{CI}}(t,w) \leq (1 - \boldsymbol{\mathcal{R}}(t_0,t))\,\boldsymbol{\mathcal{CI}}(t_0, b(t_0)) & \leftarrow \text{Alignment} \\ \boldsymbol{\mathcal{CM}}(t,w) \leq \boldsymbol{\mathcal{CM}}^{\star} & \leftarrow \text{Self-decarbonization} \\ \boldsymbol{\mathcal{GI}}(t,w) \geq (1 + \boldsymbol{\mathcal{G}})\,\boldsymbol{\mathcal{GI}}(t, b(t)) & \leftarrow \text{Greenness} \\ 0 \leq w_i \leq \mathbb{1}\left\{\boldsymbol{\mathcal{CM}}_i(t) \leq \boldsymbol{\mathcal{CM}}^{+}\right\} & \leftarrow \text{Exclusion} \\ w \in \Omega & \leftarrow \text{Other constraints} \end{array} \right. \end{aligned} \tag{1.5}$$

where Σ is the covariance matrix of asset returns. The alignment constraint is defined using the traditional decarbonization pathway formulation based on carbon intensity. For the self-decarbonization dimension, the authors impose an absolute upper bound on carbon momentum. In general, it is common to impose that at least half of the reduction rate comes from self-decarbonization. For example, if we assume that $\boldsymbol{\mathcal{R}}(t-1,t)$ is equal to 7%, then $\boldsymbol{\mathcal{CM}}^{\star}(t)$ is set to -3.5%. Green footprint management consists of improving the green footprint of the current benchmark. Indeed, while the alignment refers to the carbon intensity $\boldsymbol{\mathcal{CI}}(t_0, b(t_0))$ of the benchmark at the baseline time t_0, the greenness refers to the green footprint $\boldsymbol{\mathcal{GI}}(t, b(t))$ of the benchmark at the rebalancing date t. The coefficient $\boldsymbol{\mathcal{G}}$ measures the rate of increase of the green footprint. A typical value is 100%, which means that investors aim to double the green footprint of their portfolios relative to the benchmark. In addition to alignment, self-decarbonization and greenness, investors see exclusionary constraints as key. They are of two types. A first set of exclusionary constraints is often implemented and concerns ESG exclusions. In this case, assets may be excluded because the issuer has a poor ESG rating or is on a blacklist of companies. The second set of exclusionary constraints concerns assets that do not meet a net zero investment policy. This second set of constraints defines the "*net zero enemies*". Here, the authors decide to impose a maximum carbon momentum. Indeed, if $\mathcal{CM}_i(t) > \mathcal{CM}^+$, then $w_i = 0$. For example, if $\mathcal{CM}^+ = 10\%$, this means that all issuers that have increased their carbon intensity beyond 10% are excluded.

As we have said, there is not just one, but many approaches to implementing portfolio alignment. For example, we can consider several variants of the optimization problem (1.5). First, we can change the objective function. Instead of using a benchmark portfolio such as a stock index, we can use an initial portfolio w_0 that we want to adjust to satisfy the net zero constraints. w_0 can be an active portfolio defined by the fund manager or a systematic portfolio derived from a quantitative process. For example, this type of optimization process is used to transform an equity multi-factor portfolio into a net-zero equity multi-factor portfolio. Instead of using the tracking error variance, the risk measure can be the standard mean-variance utility function, which may or may not include sustainability preferences [6, 8, 18]. Second, we can use an objective function that depends on the active share:

$$\mathcal{AS}(w \mid b(t)) = \frac{1}{2}\sum_{i=1}^{n} |w_i - b_i(t)|$$

We can combine the stock-based active share, the sector-based active share, and the country-based active share to construct the objective function. For example, this is the approach taken by the S&P PAB indices, which use the following objective function[6]:

$$\frac{1}{n}\sum_{i=1}^{n}\frac{(w_i - b_i(t))^2}{b_i(t)} + \frac{1}{n_{\mathcal{S}ector}}\sum_{s=1}^{n_{\mathcal{S}ector}}\frac{(w_s - b_s(t))^2}{b_s(t)} + \frac{1}{n_{\mathcal{C}ountry}}\sum_{c=1}^{\mathcal{C}ountry}\frac{(w_c - b_c(t))^2}{b_c(t)}$$

where $w_s = \sum_{i \in s} w_i$ and $b_s(t)$ are the sector weights of the portfolio and benchmark, and $w_c = \sum_{i \in c} w_i$ and $b_c(t)$ are the country weights of the portfolio and benchmark. The third approach is to use the multi-period portfolio optimization method proposed by [12] and solved by [13].

[6]The choice of the $\mathcal{L}_2$ norm instead of the $\mathcal{L}_1$ norm to define the active share is due to the tractability of the objective function and, in particular, to its quadratic property. In fact, as explained by [19], from an industrial point of view, it is important to cast portfolio optimization problems into quadratic programming problems in order to obtain numerical solutions and avoid convergence and computational issues.

Regarding the alignment constraint, two different approaches can be used. First, we can replace the carbon intensity with the carbon budget [11], which is the sum of the carbon emissions of the portfolio between two dates t_1 and t_2:

$$\mathcal{CB}(t_1, t_2, w) \leq \int_{t_1}^{t_2} \mathcal{CE}(t, w(t)) \, \mathrm{d}t$$

In this case, we want the carbon emissions of the portfolio between the base date t_0 and the target date $t^\star$ not to exceed a given carbon budget:

$$\mathcal{CB}(t_0, t^\star, w) \leq \mathcal{CB}^+(t_0, t^\star)$$

In most cases, the maximum carbon budget is calculated using a global net-zero scenario[7]:

$$\mathcal{CB}^+(t_0, t^\star) = \mathcal{CE}(t_0, b(t_0)) \int_{t_0}^{t^\star} (1 - \mathcal{R}(t_0, t)) \, \mathrm{d}t$$

The alignment constraint between two rebalancing dates t and $t+1$ becomes:

$$\mathcal{CB}(t_0, t+1, w) - \mathcal{CB}(t_0, t, w) \leq \mathcal{CB}^+(t, t+1) := \mathcal{CB}^+(t_0, t+1) - \mathcal{CB}^+(t_0, t) \tag{1.6}$$

The difficulty is modeling the future carbon emissions between the current date t and the next rebalancing date t. For instance, we can use the carbon trend model. Another solution is to assume that carbon emissions are constant between t and $t+1$, which is acceptable if we consider annual periods. In this case, the constraint (1.6) reduces to:

$$\mathcal{CE}(t, w) \leq \mathcal{CB}^+(t, t+1) := (1 - \mathcal{R}(t_0, t)) \, \mathcal{CE}(t_0, b(t_0))$$

The carbon budget approach is then equivalent to a carbon emissions approach and has been proposed by [7]. The second approach is to define sectoral decarbonization pathways rather than a global one. Indeed, as we have said, we need to differentiate some sectors because they are key to achieving a low-carbon economy. This is the case of utilities, for example. [5] then propose to use a specific alignment constraint for the utilities sector and a global alignment constraint for the other sectors.

The self-decarbonization constraint can also be measured using the implied temperature rating. In this case, a temperature score is calculated for each issuer using multiple metrics: historical carbon emissions, carbon trends, issuer reduction targets, market-based climate scenarios, and so on. The idea is to compare the historical trajectory and its trend, the issuer's announced carbon targets, and the net-zero decarbonization scenario. The assessment of the company's future trajectory then has three dimensions: (historical) participation, ambition and credibility. The temperature score is then converted into

[7]For example, this could be the IPCC or IEA scenario.

an implied temperature score $\mathcal{T}$. For example, if $\mathcal{T} \leq 2°C$, this means that the company's decarbonization trajectory is compatible with a climate scenario of 2°C or less. Conversely, if $\mathcal{T} \geq 4°C$, this implies that the company is making no effort and is participating in a world with a temperature anomaly of 4°C. By assuming that the portfolio's temperature rating is the weighted average of the issuers' temperature ratings, self-decarbonization can be controlled by imposing an upper bound on the portfolio's temperature rating.

The greenness dimension of the net zero pathway is certainly the most difficult component to model and incorporate into the portfolio. While the decarbonization dimension is an exclusion process to avoid high-carbon issuers, the green dimension is a selection process to finance the issuers necessary to achieve a low-carbon economy. The decarbonization dimension is then implemented using a backward-looking framework, as it is based on past carbon intensity or emissions. In contrast, the green dimension should be implemented using a forward-looking framework, as it should be based on the future contribution to the net zero transformation. [3] chose to model the green dimension using the green revenue share. However, this is a current measure of green intensity. A better measure would be green capex, but data on this metric are not really available or noisy today[8]. Of course, this situation will improve with the new CSRD reporting and the implementation of the EU green taxonomy, but these regulations are European, which means that we will not have the data for many American, Japanese and emerging market companies. This is a real problem when implementing a net zero policy for large global indices such as the MSCI ACWI IMI Index. Sometimes the green dimension is captured by the green-to-brown ratio, but this measure has many biases because it depends on both brown and green activities[9]. It is a relative measure and does not indicate the absolute green intensity of the portfolio.

The next set of constraints is present in all alignment portfolio construction and defines the exclusion policy. It is a source of significant tracking error variance. The idea is to define a list of issuers, sectors, or activities that are inconsistent with a net zero investment policy. For example, the PAB label implies the exclusion of fossil fuel companies that derive 1%, 10%, and 50% or more of their revenues from coal, oil, and natural gas exploration or processing, respectively. Another example is the exclusion of power generation companies that generate electricity above a certain threshold, typically above 100 gCO_2e/kWh. In addition to these activity exclusions, we also find ESG exclusions for some sectors, such as controversial weapons and tobacco. The last type of exclusion concerns issuers for many reasons. They may be excluded because they are involved in ESG controversies, they do not respect social norms (UN Declaration of Human Rights, ILO Declaration and UN

[8]It is also the case of many climate risk measures such as the scope 3 upstream and downstream emissions, whose quality is very poor, both those reported by companies and those estimated by ESG rating agencies.

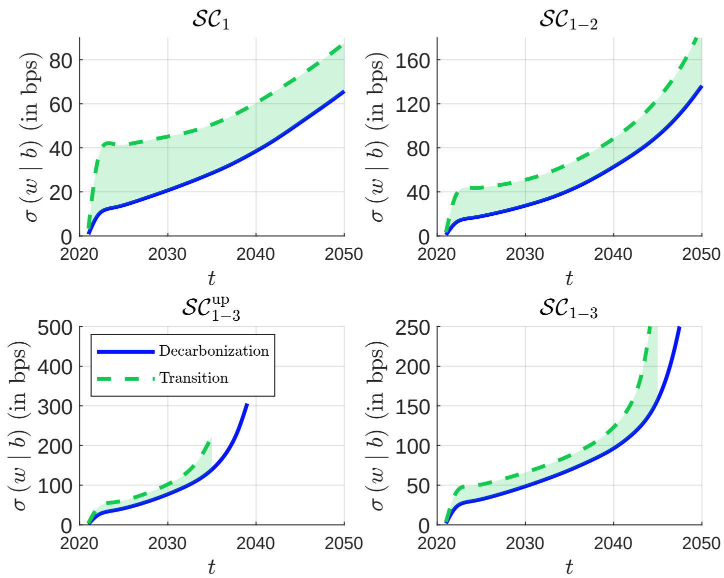
[9]This ratio compares the amount of green investment or financing to the amount of brown investment or financing.

Global Compact), they have a low ESG score, etc. They may also be excluded because they have a high carbon momentum or temperature score. Typical values are $\mathcal{CM} \geq 10\%$ and $\mathcal{T} \geq 4°\text{C}$.

The last set of constraints is necessary to control the active bets of the optimized portfolio. In fact, the optimization typically concentrates the allocation in a few stocks, a few sectors, and a few countries. Without these constraints, the portfolio is not diversified and has too many sector and country biases. Thus, [15] uses six diversification constraints to construct its PAB indexes. For example, the active country and sector weights cannot deviate by more than $\pm 5\%$ from the country and sector weights in the parent index. The active stock weight is limited to $\pm 2\%$ with an upper limit that it cannot exceed 20 times the weight in the parent index. Thus, for a stock with weights of 0.01%, 1% and 5% in the parent index, the upper limits are 0.2%, 3% and 7%, respectively. [3] use the following standard constraints, which are classic in the ETF market: $w_i \leq 10 b_i$ and $b_s/2 \leq w_s \leq 2 b_s$. The first constraint imposes that the stock weighting w cannot exceed 10 times the weighting b_i in the benchmark portfolio, while the second constraint imposes that the sector allocation w_s cannot be less than half and greater than twice the sector allocation b_s in the benchmark portfolio.

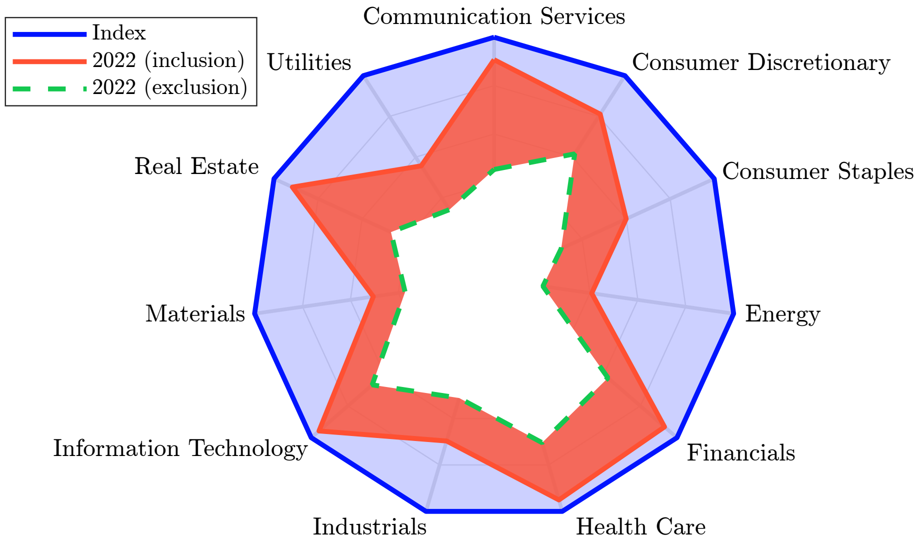
Figures 1.2 and 1.3 are taken from [3] when implementing the PAB decarbonization pathway, the self-decarbonization constraint with $\mathcal{CM}^\star = -5\%$, the greenness constraint with $\mathcal{G} = 100\%$, and the diversification constraint on the MSCI World index. The first figure shows the relationship between time t and the tracking error volatility $\sigma(w(t) \mid b(t))$, measured in bps, considering several scopes of emissions (Scope 1, Scope $1+2$, Scope $1+2+3$ upstream, Scope $1+2+3$). The figure also shows the decomposition between the decarbonization and transition dimensions. The results of these simulations clearly show that the transition dimension entails significant and additional costs. Moreover, there may be no solution to the optimization problem by 2050, especially if the carbon footprint is based on upstream/downstream Scope 3 emissions. Of course, all these results are very sensitive to the choice of the green multiplier $\mathcal{G}$ and the carbon threshold $\mathcal{CM}^\star$. In practice, many constraints are used to construct net-zero portfolios, especially exclusion constraints, which imply that the portfolio is more concentrated than the benchmark. Therefore, we may face not only diversification risk, but also liquidity risk. These risks will be reduced if the economy decarbonizes in the coming years. However, we are not immune to the possibility that carbon emissions will continue to rise in the short term. In this case, solutions will be very sensitive to the gap between the carbon target of net-zero portfolios and the carbon footprint of the economy. Figure 1.3 illustrates the shrinkage risk of the investment universe in the first year of PAB implementation when excluding or including issuers with a positive carbon momentum ($\mathcal{CM}^+ = 0\%$). The blue area shows the reduction of the investment universe when the optimization process (1.5) is implemented without the exclusion policy. The red area shows the additional reduction of the investment universe when the op-

FIGURE 1.2: Tracking error volatility of net-zero portfolios (MSCI World, June 2022, PAB, $\mathcal{G} = 100\%$, $\mathcal{CM}^{\star} = -5\%$)



Source: MSCI, Trucost & [3].

FIGURE 1.3: Universe shrinkage of net-zero portfolios (MSCI World, June 2022, PAB, $\mathcal{G} = 100\%$, $\mathcal{CM}^{\star} = -5\%$, Scope $\mathcal{SC}_{1-3}$, $\mathcal{CM}^{+} = 0\%$)



Source: MSCI, Trucost & [3].

timization process (1.5) is implemented with the exclusion policy. The effect of exclusions is very important.

What lessons can we learn from these simulations? First, reducing a portfolio's carbon footprint is an investment process that is long financials and short energy, industrials, materials and utilities, even after accounting for Scope 3 emissions. In contrast, increasing a portfolio's green footprint is an investment process that is long industrials and utilities. This is a dilemma, especially for the utilities sector. This apparent contradiction explains the increase in active risk of net-zero portfolios. Managing decarbonization and transition at the same time is not an easy task. Second, exclusion policy can have a big impact on portfolio construction, especially if we stack multiple layers of exclusion. Being too conservative can lead to having no solution for portfolio optimization. There is a real risk that existing net zero investment processes may not survive in the future, especially if the decarbonization rate of the economy is not sufficient. Third, while portfolio decarbonization is primarily an exclusion process, portfolio alignment is also a selection process. This third point is critical because investors take a lot of time to define exclusion policies, but the alignment to a net-zero scenario also requires selecting and investing in the issuers that will transform the high-carbon economy into a low-carbon economy.

1.3.2 Corporate bond portfolios

Managing a portfolio of corporate bonds is very similar to managing a portfolio of stocks, except that the measure of risk is completely different. For example, [3] use the following optimization problem:

$$w^{\star}(t) = \arg\min \frac{1}{2} \sum_{i \in b(t)} \left| w_i - b_i(t) \right| + \varphi \sum_{s=1}^{n_{\mathcal{S}ector}} \left| \sum_{i \in s} \left(w_i - b_i(t) \right) \mathrm{DTS}_i \right| \tag{1.7}$$

$$\text{s.t.} \quad \begin{cases} \boldsymbol{\mathcal{CI}}(t,w) \leq \left(1 - \boldsymbol{\mathcal{R}}(t_0,t)\right) \boldsymbol{\mathcal{CI}}(t_0, b(t_0)) & \leftarrow \text{Alignment} \\ \boldsymbol{\mathcal{CM}}(t,w) \leq \boldsymbol{\mathcal{CM}}^{\star}(t) & \leftarrow \text{Self-decarbonization} \\ \boldsymbol{\mathcal{GI}}(t,w) \geq \left(1 + \boldsymbol{\mathcal{G}}\right) \boldsymbol{\mathcal{GI}}(t, b(t)) & \leftarrow \text{Greenness} \\ 0 \leq w_i \leq \mathbb{1}\left\{ \boldsymbol{\mathcal{CM}}_i(t) \leq \boldsymbol{\mathcal{CM}}^{+} \right\} & \leftarrow \text{Exclusion} \\ \sum_{i=1}^{n} \left(w_i - b_i(t) \right) \mathrm{MD}_i = 0 & \leftarrow \text{MD constraint} \\ w \in \Omega & \leftarrow \text{Other constraints} \end{cases}$$

where DTS_i and MD_i are the duration-times-spread and modified duration factors. Compared to the equity optimization problem (1.5), the objective function is the sum of the active share and the duration-time-spread active risk. In addition, the bond optimization problem requires that the optimized portfolio and the benchmark have the same modified duration.

As with equity portfolios, there are many variations of the optimization problem (1.7). For example, we can include a modified duration risk measure directly in the objective function, and S&P combines the stock-based active share and the sector-based active share to construct the objective function of the iBoxx EUR Corporates Net Zero 2050 Paris-Aligned ESG Index. The above discussion of different constraints also applies to corporate bonds.

The conclusions we draw for equity portfolios remain valid for corporate bond portfolios. However, we find that it is easier to construct a net-zero bond portfolio than a net-zero equity portfolio. This is because the investment universe is larger for corporate bonds and the active risk of MD and DTS can be better controlled than the variance of the tracking error. Another reason is the impact of the primary market, which is small in equity markets but significant in bond markets. As bonds mature, they are replaced by new bonds that are greener. So the primary market helps to achieve net zero in corporate bonds.

1.4 The core-satellite approach

We have seen that 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. [5] propose a core-satellite strategy, where 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.

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 core portfolio is more of a top-down allocation process and exclusion strategy, where the central climate risk metric is carbon intensity. The goal of the second sub-problem is to contribute to increasing the green footprint of the economy. The satellite portfolio is more of a bottom-up allocation process and asset selection strategy, where the central climate risk metric is green intensity. This approach also has the advantage of making the allocation between the two net-zero strategies clear. Of course, the allocation to the satellite can be dynamic and change over time as the world and economy progresses toward net zero.

1.4.1 The core portfolio

The core-satellite portfolio can be applied to equity, fixed-income or multi-asset classes. For equity and fixed-income asset classes, we can use the optimization problems (1.5) and (1.7) without including the greenness constraint (and also the self-decarbonization constraint). For example, the equity or fixed-income core portfolio can be a CTB index portfolio. In the case of multi-asset strategies, the solution is to allocate between an equity core portfolio and a fixed-income core portfolio. The allocation process is generally standard in the multi-asset class and can be a mean-variance optimized, constant-mix weighting or risk parity process [20].

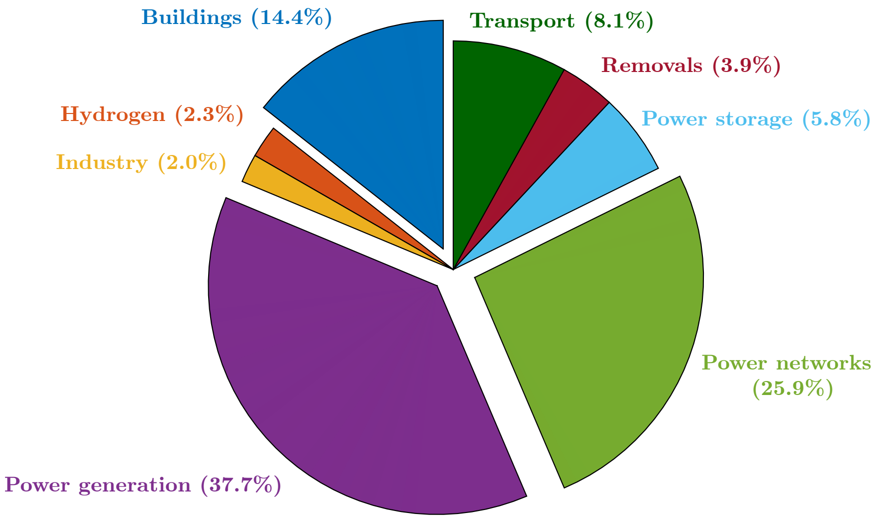
1.4.2 The satellite portfolio

The construction of satellite portfolios is more complex. Indeed, while the core portfolio aims to implement decarbonization policies, the satellite portfolio aims to finance the transition to a low-carbon economy and monitor green intensity. By definition, the core portfolio can be seen as an exclusion process applied to a traditional investment portfolio, while the satellite portfolio can be seen as a selection or asset-picking process. As the core-satellite approach is mainly implemented in strategic asset allocation or multi-asset portfolios, the investment universe is diversified and typically consists of the following asset classes: (1) green, sustainability and sustainability-linked (GSS) bonds, (2) green stocks, (3) green infrastructure and (4) sustainable real estate.

In order to determine more precisely the asset universe of the satellite portfolio, we need to understand the funding requirements of the net zero transition. According to [14], 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. 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 [10]. Figure 1.4 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.

Because the satellite portfolio is invested in the few sectors necessary to achieve net zero, it is far from a traditional investment portfolio. Therefore, the satellite portfolio has a higher active risk relative to a classical benchmark than the core portfolio. [5] estimated that the tracking error volatility of the satellite portfolio is about 10 times the tracking error volatility of the core portfolio. They also found that the tracking error volatility of a net-zero core-satellite portfolio is currently about 3% for a 60/40 constant-mix strategy.

FIGURE 1.4: Net zero capital investments



Source: [10] & Authors' calculations.

1.5 The case of sovereign bond portfolios

The case of government bonds is studied by [4]. As for corporate bonds, the integrated approach[10] for sovereign bonds consists of several steps: (1) we need to define the decarbonization scenario at the country level; (2) we can assess the self-decarbonization of a country by considering the government's credible commitments and decarbonization plans towards a low-carbon economy; (3) a specific green intensity measure needs to measure the country's contribution to the climate transition and its greenness.

In addition to the IEA net-zero scenario, we can also choose the NGFS net-zero scenario. An important point is the distinction between advanced and developing economies. Another difference with corporate bonds is the definition of the scope of emissions in particular the choice between production-based and consumption-based emissions. If we prefer a carbon intensity measure, the normalization variable can be population, GDP or public debt. Using data on carbon emissions and commitments, [4] also derived four types of forward-looking metrics: (1) carbon trend, (2) nationally determined contribution, (3) NDC ambition, and (4) NDC fulfillment. These metrics can be combined to measure country's self-decarbonization. For the green intensity, the most com-

[10]In the core-satellite approach, the satellite consists of green government bonds.

mon approach is to measure the share of renewable electricity in the country or the share of government spending on renewable electricity.

Simulations show that it is more difficult to build a net-zero government bond portfolio than a net-zero corporate bond portfolio. There are several reasons for this. The first reason is the limited number of countries compared to the number of companies. Therefore, we can quickly and dramatically shrink the investment universe. The second reason is the impact of the decarbonization dimension, because there are not many countries that have decarbonized their economies. In fact, we find that companies can change their carbon footprint faster than countries. The last reason is the liquidity issue that net-zero portfolios raise. In fact, some countries, such as the United States, have a significant share of the government bond market, and their bonds are very liquid. So a net-zero portfolio generally implies a reduction in liquidity. Managing this issue, the high active bets and the idiosyncratic risks of net-zero strategies is then a challenge and this explains why these strategies are less popular in the government debt market than in the corporate debt market.

1.6 Conclusion

The previous empirical results for equities, corporate bonds, and sovereign bonds suggest the following lessons. First, the solution is parameter and data sensitive. In particular, we need to be careful in choosing the carbon scope metric to assess the decarbonization rate. A net-zero investment policy only makes sense for a closed system. Therefore, Scope 3 and consumption-based emissions need to be taken into account to align a portfolio with a net-zero scenario. The problem is that we see a lack of data reliability on these indirect emissions today. Similarly, the solution is highly dependent on the green intensity target and the level of self-decarbonization we want to achieve. Then we have to be careful because there may be no solution to the optimization problem in the medium term. The question of no solution depends on the relative speed of the portfolio's decarbonization path relative to the economy's decarbonization path and the initial starting point.

The second key finding is that portfolio decarbonization and net-zero construction lead to different solutions. In particular, decarbonizing a portfolio is easier than constructing a net-zero portfolio. We find that decarbonizing along CTB or PAB pathways never leads to exploding tracking errors by 2030. In fact, the real problem with decarbonization is the diversification and liquidity risk that an investor may face. These results are amplified when we add the transition dimension to the optimization program. In addition to higher tracking risk, there is no guarantee that there will always be a solution. Moreover, the introduction of the transition pillar highlights the difficulty of choosing an appropriate set of constraints for net-zero portfolios, as some metrics may be negatively correlated with others. Portfolio decarbonization is systematically a strategy that is long financial issuers and short energy, materials and utilities issuers. Therefore, we have a situation where the transition dimension of a decarbonized portfolio is weaker than that of the benchmark portfolio, as green solutions are also located in carbon-intensive sectors. It is therefore crucial to distinguish between issuers with a high carbon footprint that will not participate in the transition and those that will reduce their carbon emissions and find low-carbon solutions.

The third key finding is that portfolio decarbonization and alignment are two processes of exclusion. This means that it is quite impossible to achieve net zero alignment without allowing the algorithm to exclude companies (or countries) from the benchmark. For example, the optimization program will generally not find a solution if it imposes non-zero lower bounds. As a result, some key players in the transition, such as energy and utility companies, unfortunately disappear. Furthermore, imposing sector neutrality can lead to similar problems in finding a solution.

The final lesson is that it is easier to implement net zero in bonds than in equities. At first glance, this result may seem surprising, since there is no reason why net zero should affect the equity and bond markets differently. In fact, there are two possible explanations. First, the structure of equity and bond indexes is different, with the latter having a more balanced allocation across sectors and a high exposure to financial issuers. Second, bond indexes are strongly influenced by new fresh capital, while equity indexes are sticky to the stock of existing capital. This is because the primary bond market is very active, which implies a significant impact on the secondary market. Indeed, bonds mature and are replaced by new greener bonds. The primary market then helps to achieve net zero in bonds. This is not the case in the stock market, where IPOs and capital increases are only a small part of the secondary market. This means that portfolio holdings change faster for bond indexes than for equity indexes. Therefore, the greenness of bond indexes increases faster than the greenness of equity indexes. All of these factors suggests that the cost of implementing net zero investments relative to traditional investments will be higher for equity portfolios than for bond portfolios, and that the bond market will benefit more quickly from the transition to a low-carbon economy.

Beyond these empirical results, there is another important point that is missing from our analysis. This is the issue of engagement. Indeed, it may be surprising to talk about net zero investing without integrating this dimension into portfolio construction. The reason is that engagement is difficult to model quantitatively. Nevertheless, [9] has recently developed a quantitative framework and an objective metric called distance-to-exit that can help identify the most critical companies that investors need to engage with when building a net-zero portfolio. Whatever the approach, the results of engagement must of course be integrated into the net zero investment policy. This can be done, for example, by adjusting carbon and/or green footprints. Engagement is also important because dialogue with issuers also helps investors understand the industrials issues surrounding net zero. Too often, investors assume that net zero investing is a matter of overweighting or underweighting a benchmark. This is an oversimplified view of net zero. For example, real asset investors know the importance of understanding the industrial processes involved in a net zero transition. Again, this ties into the top-down versus bottom-up debate about net-zero portfolio construction. Even if you take a top-down approach (which this chapter largely does), it is important to ensure that the investment of each stock in the portfolio has a bottom-up rationale.

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