Sustainable Investing and Climate Transition Risk: A Portfolio Rebalancing Approach

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KEY FINDINGS

- Under a strong market neutrality approach, it is not possible for central banks, including the European Central Bank, to reduce climate transition risk in their portfolios.
- The authors propose a weaker market neutrality approach that enables the construction of portfolios with lower climate transition risk and yet limited market impact.
- They show that GHG emissions and ESG alone are not sufficient to inform climate-aware portfolio rebalancing, and introduce a complementary measure of transition risk to overcome such limitation.

ABSTRACT

The authors studied how greenness can be combined with other investment criteria to construct sets of corporate bond portfolios with decreasing exposure to climate transition risk. They apply the methodology to the European Central Bank's asset purchase program. They define a weaker market neutrality principle as investing proportionally to the bond amount outstanding within Climate Policy Relevant Sectors. The portfolio rebalancing leads to a 10% reduction of exposure to climate transition risk. Then, the authors studied the relationship between bonds' rebalancing and issuers' environmental, social, and governance (ESG) characteristics and greenhouse gas (GHG) emissions. Bonds issued by firms with low (high) ESG risk and GHG emissions are more likely to be bought (sold) in the rebalancing. Finally, they analyzed the implications of portfolio rebalancing on financial markets, finding that changes in yields would be limited to less than 80 basis points on individual bonds. The approach can contribute to inform climate-aware portfolio rebalancing and sustainable investment strategies.

Decreasing portfolio exposure to climate transition risks—that is, the risks emerging from a disorderly low-carbon transition—have become a main concern for a growing number of investors and supervisors (Karagozoglu 2021; Kreibiehl et al. 2022; NGFS 2019).[1] Investors have been recommended by central banks and financial regulators to disclose and assess climate risks in their portfolios (BOE 2022; EBA 2022; ECB 2022; TCFD 2017). These considerations apply to central banks as well. In the European Union, a debate has emerged among scholars and practitioners on whether and how the European Central Bank (ECB) could foster climate disclosure and assure that climate risks are adequately incorporated into

[1] For example, see "Larry Fink's 2021 Letter to CEOs," https://www.blackrock.com/corporate/investor-relations/larry-fink-ceo-letter.

its risk management and into that of the supervised financial institutions (Schnabel 2021). As investors, central banks are also subject to investment criteria in their asset purchases, such as the so-called market neutrality principle, that is, following an investment strategy that reflects the proportion of assets' values in the market. As the ECB President has recently stated, however, "The ECB must question whether mirroring the composition of the bond market in its asset purchases is appropriate in light of climate risks" (Arnold 2020). So far, however, the market neutrality principle has been a guiding principle that explicitly constrains the ECB's purchasing strategy.[2]

In this regard, to what extent an investor can rebalance their portfolio in order to decrease the exposure to climate transition risk remains an open question. In this article, we study how greenness and other investment criteria can be combined to construct sets of portfolios with decreasing exposure to climate transition risk.

We focus our analysis on a portfolio of corporate bonds and study how it can be rebalanced, shifting weights from issuers that are more exposed to climate transition risk to issuers that are less exposed to it, while respecting a set of sustainability and investment criteria. We thus propose a climate tilting strategy for climate-aware portfolio rebalancing. Despite tilting has attracted growing attention in the literature (e.g., BOE 2021; Schoenmaker 2021), a formalization and implementation of climate tilting is still missing.

Most analyses so far have had a narrow focus of transition risk, proxied by greenhouse gas (GHG) emissions. We complement these analyses by taking into account the bond issuers' energy technology profile, which plays a main role in the firms' alignment to climate objectives and drives the forward-looking exposure to transition risk. With this aim, we consider the carbon intensity of the energy technologies and their role in the low-carbon transition (e.g., we distinguish between coal, oil, and gas within the energy sector). Our motivation to combine GHG with technology information stems from the well-known limitations of GHG information taken alone. The literature has shown that information about GHG emissions is relevant for banks' lending decisions (Herbohn, Gao, and Clarkson 2019), for investors' risk-adjusted returns (Liesen et al. 2017; Bolton and Kacperczyk 2021), and for net-zero portfolio rebalancing (Bolton, Kacperczyk, and Samama 2022). However, the sustainability performance of an investment is also highly sensitive to the type of indicators used (Görgen, Jacob, and Nerlinger 2021; Scholtens 2010). Moreover, it has been increasingly recognized that GHG emissions accounting faces some limitations (Busch, Johnson, and Pioch 2020), particularly in the context of Scope 3 emissions (Ducoulombier 2021; EU Technical Expert Group on Sustainable Finance 2019).

Available GHG emission intensity data display limited reliability and comparability across issuers. For instance, the Scope 3 emission intensity of otherwise similar European car manufacturers (e.g., Stellantis NV and Volkswagen AG) can vary by a factor of more than 30 times due to differences in reporting models. Thus, using GHG emission intensity to decide how to shift weights across issuers can be misleading.

Moreover, rebalancing a portfolio with the aim of minimizing GHG emissions regardless of sectoral considerations can lead to economically unviable results.

Similar concerns have been raised about environmental, social and governance (ESG) ratings and ESG data in general, in terms of limited convergence (Berg, Kölbel, and Rigobon 2022; Dimson, Marsh, and Staunton 2020), or biases stemming from a lack or abundance of data (Chen, von Behren, and Mussalli 2021; Kotsantonis and Serafeim 2019).

[2] In July 2022, the ECB announced its aim to gradually decarbonize its bond portfolio, by following a tilting strategy when reinvesting upcoming redemptions. The ECB expects the measures to apply from October 2022, but no further detail has been published to date (https://www.ecb.europa.eu/press/pr/date/2022/html/ecb.pr220704~4f48a72462.en.html).

We apply our analysis to the corporate bond portfolio of the ECB within the Pandemic Emergency Purchase Program (PEPP).[3,4] In particular, we study to what extent the market neutrality principle constraints the ability of the ECB to integrate climate transition risk in its monetary policy.

We start by defining a strict market neutrality principle, which requires investment in corporate bonds that is proportional to the securities' amount outstanding in the market. The rationale behind market neutrality is to minimize the impact on relative prices within the eligible universe of assets (Hammermann et al. 2019). This constraint adds up to the criteria that define the eligible bond universe.

We demonstrate analytically that under a strict market neutrality principle, the ECB corporate bond portfolio is completely determined and there is no room to reduce its climate transition risk. Thus, if markets do not fully price it, then it is not possible to reconcile the market neutrality principle with climate change considerations.

Second, we define a weaker market neutrality principle, in which the criterion to invest proportionally to the amount outstanding of the issuer is relaxed into investing proportionally to the amount outstanding within economic sectors. To define these sectors, we follow the Climate Policy Relevant Sector (CPRS) classification developed by Battiston et al. (2022).[5] The CPRS classify economic activities at a high degree of granularity (e.g., NACE 4-digit level) into unique and decreasing classes of exposure to climate transition risk. By considering not only the GHG emissions profile of an activity but also its energy technology profile, its business model, and the climate policy sensitivity, the CPRS classification contributes to overcoming some of the limitations of GHG accounting. Furthermore, it is applicable to all investors and jurisdictions. For these reasons, it has been increasingly used by financial supervisors to assess transition risk (e.g., Battiston et al. 2020; EBA 2020; ESMA 2020).

We show analytically that under the weaker neutrality principle, the ECB can rebalance the portfolio in order to lower its exposure to climate transition risk, while respecting all other investment criteria. We propose a tilting methodology which can be easily applied to adjust the portfolio to reduce climate transition risk. The weaker neutrality principle implies investment that is proportional to the outstanding amount of bonds issued by companies in a given CPRS but it leaves some room (under all other constraints) to increase the amounts invested in companies that are involved with activities less exposed to transition risk. For instance, within the fossil fuel sector, exposures to firms with a higher share of gas relative to coal in their production increase. Similarly, in the electricity sector, exposures to firms with a higher share of renewable sources increase. Consistent with the literature (Avramov et al. 2022; Papoutsi, Piazzesi, and Schneider 2021), one could construct a risk factor from the proposed measure. Then, the central bank can go long or short this factor in order to improve its climate transition risk profile.

This weaker market neutrality principle allows now for some margin of optimization of climate transition risk performance. Thus, we develop an optimization algorithm that compares pairs of corporate bonds in terms of exposure to climate transition risk, within a given CPRS, and shifts a small fraction of weight from one bond to the other if the change meets all the criteria.

By means of numerical simulations, we produce samples of viable portfolios under this weaker neutrality principle and we study their characteristics. We find that the rebalancing can achieve an aggregate reduction of exposure to economic activities

[3] See https://www.ecb.europa.eu/mopo/implement/pepp/html/index.en.html.

[4] Despite the ECB's announcement to stop net asset purchases under the PEPP from March 2022, the question of transition risk within bonds already bought remains.

[5] The CPRS classification is open access online at the following link: https://www.finexus.uzh.ch/en/projects/CPRS.html.

with high climate transition risk of about 10% and a reduction of total aggregate GHG emissions of about 6%.[6]

Furthermore, we find a relationship between the effects of rebalancing under weaker market neutrality and alternative measures of transition risk. We perform an econometric analysis to study the relationship between the bonds affected in the rebalancing and the characteristics of the issuers, in terms of ESG scores and GHG emissions. We find that bonds issued by firms with lower (higher) ESG risk are more likely to be bought (sold) in the rebalancing, while bonds issued by firms with higher GHG emissions are less likely to be bought.

Finally, we analyze the potential consequences of a portfolio's rebalancing on financial markets. Results show that changes in bond yields would remain limited to less than 80 basis points on individual bonds and be almost negligible. In order to study the impact of the rebalance, we leverage existing estimates in the literature (Abidi and Miquel-Flores 2018). Other approaches have been proposed by scholars, such as Arce, Mayordomo, and Gimeno (2020), Grosse-Rueschkamp, Steffen, and Streitz (2019), and Todorov (2020).[7]

Our analysis provides an approach to climate-aware portfolio rebalancing and implications in terms of transition risk, ESG profile, and market impact. This, in turn, can inform sustainable investment strategies.

Our work contributes to three main strands of the literature. First, we clarify open questions regarding market neutrality in central banks' portfolios and its impact on the climate transition risk profile of bond purchases. Second, we contribute to the broader discussion of measuring the greenness and climate transition risk of an activity. Third, we provide a portfolio rebalancing approach designed to help reduce transition risk considering allocation constraints.

This article is structured as follows. First, we describe the methodology, considering the criteria of asset purchase programs and the notion of climate transition risk. Second, we provide the main analytical results under the notions of strong and weaker market neutrality. Third, we present the dataset for the empirical analysis. Fourth, we report the empirical results on the construction of alternative portfolios with lower level of exposure to climate transition risk. Fifth, we discuss the relation between the effects of portfolio rebalancing and alternative measures of transition risk.

BACKGROUND INFORMATION

Central Banks' Asset Purchase Programs

Central banks have implemented a set of unconventional monetary policy measures, including asset purchase programs, to mitigate the economic impacts of the 2008 financial crisis and of the COVID-19 crisis.[8]

We apply our methodology to the corporate bond portfolios of the ECB originated from the Asset Purchase Program (APP). Within it, two specific measures have targeted corporate debt: the Corporate Sector Purchase Program (CSPP, from 2016 onward) and the Pandemic Emergency Purchase Program (PEPP, from 2020 onward).

[6] The size of the rebalancing is quantified by the total weight moved away from sold bonds in the context of this study. A rebalancing of 6% means that 6% of the portfolio weight has been moved from sold bonds to bought bonds.

[7] An estimate of the yield effect of the PEPP on bonds with different level of exposure to transition risk is left for further studies.

[8] While many central banks are reducing or stopping their net purchases in light of the high-inflation environment of late 2021 and 2022, the question of transition risk in the portfolio they have already accumulated remains.

EXHIBIT 1

Eligibility Criteria for the CSPP/PEPP Programs

Number	Dimension	Criteria
1	Instruments	All assets eligible under the APP are eligible under the PEPP; non-financial commercial paper is eligible since the PEPP inception for both the PEPP and CSPP
2	Maturity	Private securities must have a minimum maturity of 28 days, if they had an initial maturity of 365/366; or, if the initial maturity was more than 367 days, a maturity from 6 months up to a maximum of 30 years
3	Size Requirements	No minimum issue size requirement applies to bonds; commercial paper must have a minimum outstanding amount of €10 million
4	Rating	The first-best credit assessment for the issue, issuer or guarantor must be at minimum BBB–/Baa3
5	Sector	Private instruments must be issued by non-bank corporations
6	Domicile	The issuer must be incorporated in the euro area
7	Country Purchases	Market capitalisation provides a weighting for each of the different jurisdictions of issuance within the benchmark. In the context of the internal benchmark, the "market capitalisation" of a given issuer refers to the nominal outstanding amount of eligible bonds issued by the issuer in question as a share of the entire CSPP-eligible universe.
8	Issuer Limit	The Eurosystem applies additional limits per issuer group, following a predefined benchmark, reflecting all eligible outstanding issues. The predefined benchmark is defined by "market capitalisation" as per criterion 7.
9	Limited Purchases	The Eurosystem applies a maximum issue share limit of 70% per corporate bond on the basis of the outstanding amount.

NOTES: First column: custom enumeration of criteria. Second column: subject matter for the requirement. Third column: description of the requirement.

SOURCE: ECB's Q&As for CSPP and PEPP.

Both programs target corporate securities and share the same eligibility criteria, which are listed in Exhibit 1.[9]

Investors' Exposure to Climate Transition Risk

Climate transition risk refers here to the risk associated with a low-carbon transition in which changes in the values of financial assets are not fully anticipated or hedged by market players. There are several reasons for the lack of anticipation, including a late and sudden alignment to climate targets (e.g., 2 degrees C) due to the complexity of the policy process, as well as technological developments and social dynamics (Monasterolo 2020).

Recent literature has developed a standardized, science-based, and replicable approach to identify economic activities that are exposed to climate transition risk, that is, the CPRS classification (Battiston et al. 2022). CPRS classifies individual economic activities, identified at a highly granular level (e.g., the NACE 4-digit level), into unique classes of decreasing exposure to climate transition risk. This is important because standard classifications of economic activities do not provide direct information about the activity's exposure to climate transition risk, its energy technology mix, nor its relevance to climate policy. Thus, they are not directly applicable to assess an activity's exposure to climate transition risk.

[9] See more details on eligibility criteria for CSPP at https://www.ecb.europa.eu/mopo/implement/omt/html/cspp-qa.en.html and for PEPP at https://www.ecb.europa.eu/mopo/implement/pepp/html/pepp-qa.en.html.

The activities belonging to CPRS are identified using three main criteria:

- the direct and indirect contribution to GHG emissions (Scope 1, 2, 3);
- the activity's business and revenue model (e.g., input substitutability, role in the energy value chain);
- the relevance to climate policy implementation (i.e., their cost sensitivity to climate policy change; e.g., the EU carbon leakage directive 2003/87/EC).

Thanks to these characteristics, CPRS enables mapping transition risk information on activities into the relevant NACE 4-digits (or NAICS) code. Thus, they are flexible to adapt to the available project-based information of the financial contract or security.

CPRS levels provide different degrees of granularity based on the information available about the technology used by the company's activity and revenues composition. The most aggregate level of CPRS is defined as "CPRS Main." It yields six sectors: CPRS1-fossil-fuel, CPRS2-utility, CPRS3-energy intensive, CPRS4-buildings, CPRS5-transportation, CPRS6-agriculture. A more disaggregated level of CPRS is "CPRS2" that extends the original classification into activities with varying degree of exposure to transition risk. For instance, within transportation, activities related to road transportation are currently mostly based on the use of fossil fuels (by combustion engines), while railways transportation is largely (e.g. about 55% in Europe) based on electricity and thus, at least potentially, on renewable energy. For the sector of utilities electricity, we further use information on the energy technology used by the issuers (e.g. coal, gas, solar, wind, etc.). This granularity is important because a growing number of large firms have both high- and low-carbon business lines, which is relevant for climate transition risk.[10]

Therefore, using CPRS enables us to overcome the limits of classifications of exposures based on GHG emissions, adding a climate risk connotation. In the following, we use CPRS Main to define one of the constraints for the portfolio construction and CPRS2 as one of the criteria to lower the level of transition risk.

Analytical Results: Strong and Weaker Market Neutrality

Exhibit 1 describes the criteria adopted by the ECB in terms of both eligibility and weighting. In essence, these criteria imply that one should purchase bonds proportionally to their amount outstanding, subject to some constraints on individual issuers (e.g., residence and risk) and to some aggregate constraints (e.g., balance across EU member states). The intuition is that under such criteria, an investment strategy is market neutral, in the sense that it follows as much as possible the market composition. Therefore, we call this set of criteria *strong market neutrality,* as in Definition 1 (discussed later in this subsection). It is possible to show that under strong market neutrality, the ECB's corporate bond portfolio is completely determined; that is, the ECB has only one possible portfolio that respects all criteria at the same time. Hence, the ECB has no leeway to reduce its exposure to climate transition risk. The results are formalized in Proposition 1 (discussed later in this subsection).

While there may be a perception for this result among practitioners, to our knowledge, no formalization has been provided yet. The intuition for the proof is as follows. We assume that bond issuers can be classified in terms of certain sectors of economic activities, indexed as S, belonging to macrosectors, indexed as MS. We further assume that it is possible to attribute to each issuer a level of exposure to climate transition risk, denoted as Q_s. Later, we will use CPRS Main and CPRS2 as specific classifications, but the result holds also in general.

[10] For the latest version of the CPRS classification and its mapping into the climate scenarios of the Network for Greening the Financial System (NGFS) see (Battiston et al. 2022).

We can then establish a partial order within the macro sector; that is, it is possible to find sectors that are less exposed to climate transition risk than others. We define the risk for a portfolio P as the weighted average of the variable Q_s, denoted as Q_P. Then, given two portfolios P_1 and P_2, obtained by changing the sector composition, it is possible to test which one has a lower exposure to climate transition risk.

It emerges that a strong market neutrality implies that, given the current ECB's portfolio, there is no other feasible portfolio with lower climate transition risk.

Definition 1 (Strong market neutrality). *We speak of strong market neutrality if criteria 1–9 as defined in Exhibit 1 simultaneously hold.*

Proposition 1 (Portfolio selection under strong market neutrality). *Assuming that an investor respects all criteria under the assumption of strong market neutrality in Definition 1, their portfolio is completely determined.*

Note that the proposition does not imply that all weights are fully determined. The ECB can still decide how much to invest in a specific bond, within the limits of criteria 7 and 8. Hence, discrepancies between the universe of eligible bonds and the ECB's actual portfolio may exist; that is, there could be bonds eligible in principle but not bought by the ECB. However, these discrepancies are marginal in volume and can be ultimately attributed to factors related to domicile, issue volume, liquidity, internal risk management, or rating considerations. Moreover, the classification of issuers as public undertakings could imply limited deviations.

Because the uniqueness result of Proposition 1 is determined by the definition of strong market neutrality, we introduce a weaker definition of market neutrality in Definition 2. This definition is based on the amount outstanding at the level of sectors as opposed to the level of issuers as in Definition 1. In this study, we defined the sectors following the CPRS classification.

More precisely, we impose that the amount outstanding in each given CPRS Main sector is preserved, while the exposure to CPRS2 can vary, thus varying the exposure of the portfolio to transition risk. We demonstrate that under this weaker definition of market neutrality, the ECB can still comply with criteria 1–7 and 9 (see Exhibit 1), and simultaneously decrease its portfolio exposure to climate transition risk.

Definition 2 (Weaker market neutrality). *We speak of weaker market neutrality if criteria 1-7 and 9 as defined in Exhibit 1 simultaneously hold, while criterium 8 is substituted as follows: purchases must be proportional to the amount outstanding in each given macro sector (CPRS Main in this study).*

Under this weaker definition of market neutrality, the climate transition risk exposure of the portfolio can be reduced, as from Proposition 2:

Proposition 2 (Portfolio selection under weak market neutrality). *Assuming an investor follows market neutrality as from Definition 2, their portfolio can be rebalanced to reduce the exposure to climate transition risk.*

Data

For the empirical analysis, we combine data on the ECB's portfolio of corporate bonds with micro-data collected from multiple sources. As we analyze the portfolio at a given point in time, most variables are collected for 2020. One variable, namely capital expenditure (CAPEX), is considered from 2014 to 2020. Importantly, we work under the assumption that the ECB's portfolio respects the constraints of Definition 1, and hence, that it corresponds to the eligible universe of securities. We gather the corporate bond portfolio as published by the ECB, consisting of 1,588 bonds, issued by 332 unique issuers, as of November 6, 2020. The portfolio is purchased in the context of both the PEPP and CSPP and has a total holding volume of €243,331 million at end of October 2020.

For each bond, we gather the following variables from Refinitiv Eikon:[11]

- country of domicile,
- organization parent,
- NACE 4-digit classification,
- best of issuer or issue rating,[12]
- amount outstanding,
- green bond flag.

A crucial step in the analysis is the reclassification of selected issuers. Indeed, several bonds in the ECB portfolio are issued by financial vehicles owned by European and non-European companies. For example, the only bonds from the major oil company Shell included in the portfolio are originated by Shell International Finance BV, whose NACE code is 64.30 (*Trusts, funds and similar financial entities*), while Shell's NACE code is 19.20 (*Manufacture of refined petroleum products*). This example shows why a reclassification of the declared NACE codes is needed. Using the declared NACE classification would lead us to wrongly assign this company to the financial sector while, in reality, it is an oil major.

To overcome this problem, we perform desktop research to collect the correct information about these financial issuers, linking them to their parent companies. This enables us to gather a correct picture of the portfolio and its sector allocation, also in terms of CPRS Main and CPRS2. Similarly, we reclassify bonds that have originally incorrect NACE codes assigned.

Because our analysis takes a technological and sector perspective, quality assurance is a crucial process for the success of the rebalancing. For example, in the context of utilities, we pay attention to correctly differentiate energy generation from energy transmission, energy distribution, or water, because these activities have a significantly different climate transition risk profile.

The ECB does not publish the amount invested in each bond. Thus, we assign weights proportionally to the amount outstanding. While being a limitation, it is also the best available approach without having access to confidential supervisory data.

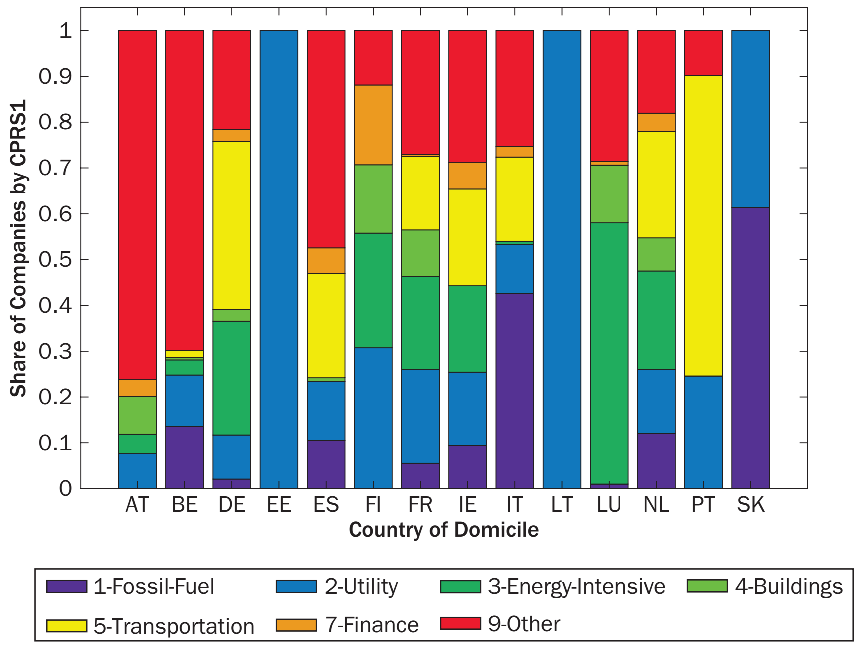
To better capture the technology profile of an issuer, we gather two additional variables from Bloomberg New Energy Finance (BNEF).[13] First, we use the variable "Exposure to New Energy" referred to as the "NEF Index" from now on. Second, we retrieve the list of renewable energy projects in Europe, and we derive a measure of CAPEX greenness, as follows:

1. The database of all renewable energy projects in Europe is gathered via BNEF. The covered variables of interest are owners, technology, date, project status, capacity, and cost. We consider only non-decommissioned and non-abandoned projects from 2014 to 2019.
2. Owners are consolidated to the first listed entity where available or to the first non-government parent when unlisted.
3. Some projects do not report the value. Thus, cost curves are estimated at the technology level using existing data for capacity and cost.
4. Missing project values are filled using exponential or cubic interpolation.
5. For each owner, CAPEX values are downloaded via Refinitiv Eikon.
6. The greenness indicator is computed over a three-year rolling window from 2016 to 2019, as $GI_y = \frac{\Sigma_{y-2,y-1,y} capex_{Green}}{\Sigma_{y-2,y-1,y} capex_{All}}$.

[11] https://eikon.thomsonreuters.com/index.html.
[12] Considering ratings as published by Standards & Poor's, Moody's, and Fitch.
[13] https://about.bnef.com/.

EXHIBIT 2

Exposure of the ECB Portfolio by Country of Domicile and CPRS Main, after Reclassification



NOTE: The horizontal axis shows country of domicile of the bond issue; the vertical axis shows share of companies by CPRS Main, after reclassification of issuers by the authors.

SOURCE: Portfolio composition as of November 6, 2020, from the ECB, available at https://www.ecb.europa.eu/mopo/implement/app/html/index.en.html, as elaborated by the authors.

Both the NEF Index and the CAPEX Greenness are used to define the greenness measure for utilities, see more below.

The composition of the ECB's portfolio is described in Exhibit 2. Exhibit 2 shows some challenges for portfolio rebalancing. Indeed, under weaker market neutrality, the ECB must maintain the CPRS Main proportion constant and cannot alter the country composition. This implies that the rebalancing will be possible for some countries, for a limited share of the portfolio weight. Nevertheless, we show that it is possible to do a rebalancing toward companies that are less exposed to climate transition risk.

We classify issuers as follows:

- For issuers other than those engaged in electricity generation (e.g. fossil fuels producers, car manufacturers, etc.) we group them based on CPRS2.
- For issuers mostly engaged in electricity generation, we proceed as follows. We group them into four classes based on their generation capacity share in renewable energy (e.g. biomass, hydro, solar, wind). We also group them into four class based on level of CAPEX greenness (see above). We then take a weighted sum of the two class ordinals and round the numbers to obtain again integers. Intuitively, companies with the highest renewable capacity and the highest investments in future renewable power plants end up in the highest category (lowest transition risk). For issuers mostly engaged in activities within utilities other than electricity generation (e.g. electricity transmission or diversified utilities such as water), we group them based on their NEF index.

As additional measures of transition risk, we collect information on science-based targets provided by the Science-Based Targets Initiative (SBTI),[14] on ESG Risk Ratings from Sustainalytics,[15] and on GHG emissions Scope 1, 2 ,and 3 from Refinitiv Eikon.[16] These variables are collected for the latest available information as of November 2020, that is, the date we downloaded the ECB's portfolio composition.

We convert the targets into an ordinary scale by considering the commitment status and the implied temperature increase that the companies have committed to in their reports and public statements. As a general rule, we assign a higher value to more ambitious commitments. The ordinary scale is as follows:

- a company with no declared commitment is assigned a value of 0;
- one with a generic commitment is assigned 1;
- a commitment to 1.5°C is assigned 2;
- a target set is assigned 3;
- a target set at 2°C is assigned 4;
- a target set at well-below 2°C is assigned 5;
- a target set between well-below 2°C and 1.5°C is assigned 6;
- and a target set at 1.5°C is assigned 7.

Given the limited availability of data about GHG emissions, in particular for Scope 3,[17] we complete our sample by manual research on annual and sustainability reports available as of November 2020. This enables us to retrieve missing information for 28 additional issuers, or 142 bonds. Finally, for selected issuers within the gas distribution activities, we estimate Scope 3 emissions and intensity using a revenue proportion to the corresponding activity averages. This step is necessary to complete the GHG emissions for a critical class of activities. A summary of data availability for GHG emissions and ESG Risk Ratings is provided in Exhibit 3.

The limitations of Scope 3 data play an important role in our analysis and justify our data reconstruction approach. Consider, for instance, Stellantis NV and Volkswagen AG, major European carmakers, with similar average fleet emissions intensity,[18] and hence a comparable profile in terms of transition risk of their fleets. While their Scope 1 and 2 emission intensities are comparable,[19] their Scope 3 intensities differ by a factor of 128. As of 2019, Scope 3 intensity for Stellantis was 12.29 tonnes/USD million while for Volkswagen it was 1,579.88 tonnes/USD million. The situation did not change in 2020, where the numbers are, respectively, 12.24 and 1,335.35.[20] This reporting bias stems from the differences in the models used for internal calculations and in the Scope of reporting, despite the existence of a common directive that explains how to calculate Scope 3 emissions, followed by VW. While we can expect the situation to improve in the future, it represents a significant issue for financial research now.

Challenges with Scope 3 data have major implications for our analysis, thus leading us to consider a different measure for transition risk as discussed in the next section and in Exhibit 4. The enhanced measure defined is then used as a quantification of transition risk for climate risk-aware portfolio rebalancing.

[14] https://sciencebasedtargets.org/about-us.

[15] https://www.sustainalytics.com/esg-ratings.

[16] We also gather the respective intensities in terms of Scope 1 and 2 only; Scope 1, 2, 3; and the calculated totals.

[17] Scope 3 information is available for only 1,089 bonds, and 154 issuers.

[18] Respectively, as of 2019, 124.80 g/km for Stellantis NV and 124.00 g/km for Volkswagen (source: Refinitiv Eikon).

[19] 28.17 tonnes/USD million for Stellantis, 27.40 tonnes/USD million for Volkswagen as of 2019 (source: Refinitiv Eikon).

[20] Nor did it change in 2021.

EXHIBIT 3

Sample Data Availability, Absolute and in Percentage, Number of Issuers, and Number of Bonds

	Data Availability Summary			
Variable	Number of Issuers	Percentage of Issuers	Number of Bonds	Percentage of Bonds
ESG Risk Ratings	290	86.57%	1,495	94.80%
Scope 1 Emissions	248	74.03%	1,302	82.56%
Scope 2 Emissions	249	74.33%	1,304	82.69%
Scope 3 Emissions	224	66.87%	1,225	77.68%
Scope 1 + 2 Emissions	261	77.91%	1,377	87.32%
Scope 1 + 2 + 3 Emissions	224	66.87%	1,225	77.68%
Scope 1 Intensity	236	70.45%	1,268	80.41%
Scope 1 + 2 Intensity	249	74.33%	1,343	85.16%
Scope 1 + 2 + 3 Intensity	212	63.29%	1,191	75.51%

NOTES: For targets, a value of zero is assigned to issuers that did not publish any. Hence, all issuers have data for this variable. Each row represents a variable of interest. In the second and third columns, the availability is described by the number and percentage of issuers, out of a total of 332 issuers. In the fourth and fifth column, the availability is described by the number and percentage of bonds, out of a total of 1,588 bonds.

SOURCE: Authors' calculations.

EMPIRICAL RESULTS

Portfolio's Exposure to Climate Transition Risk

As defined previously, climate transition risk is denoted as Q_s and depends on the sector *S*. Because it is possible to establish, within a certain macro sector *MS*, an order of climate transition risk such that $Q_{S_1} < \ldots < Q_{S_n}$, it is then possible to reach a situation where for two portfolios P_1 and P_2, it holds that $Q_{P_1} < Q_{P_2}$. As from Definition 2, we define macrosectors and sectors according to CPRS Main and CPRS2 as in Battiston et al. (2017 and 2020).

Exhibit 4 provides a summary of categories of transition risk for each CPRS Main.

Within each CPRS Main sector, issuers are grouped in categories from 1 to 5, based on their CPRS2 sector, with decreasing levels of transition risk (i.e. category 5 has the lowest risk level), as follows:

- CPRS Main 01-fossil-fuel: issuers engaged in extraction, manufacturing and sales of various fossil fuels, are grouped in categories based on CPRS2 (i.e. fuel type, here), ordered by decreasing level of transition risk.
- CPRS Main 02-utility: issuers engaged in electricity (generation, transmission, distribution, trade), sewage, water and waste. Issuers are grouped based on their CPRS2 sector and on a proxy of green investment level (see Section Data). Within electricity generation and distribution, weight transfer is allowed from non-renewable generation issuers to renewable generation issuers (see definition in Section Data), or to transmission and distribution companies. Weights for diversified utilities and water utilities remain unchanged.
- CPRS Main 03-energy-intensive: issuers engaged in selected manufacturing activities, grouped by CPRS2 sector as follows: 1-category (cement, fertilisers, agrochemicals, iron and steel, pharmaceutical); 2-category (rubber and plastics); 3-category (non-fossil mining); 4-category (electrical); 5-category (food and beverages, and other).

EXHIBIT 4

Categories of Transition Risk and Weight Rebalancing Rules

CPRS Main	Transition Risk Category	Nace Codes Examples
1-fossil-fuel	All	05.10, 05.20, 06.10, 35.22
1-fossil-fuel	1-coal-extraction	05.10, 05.20
1-fossil-fuel	2-oil-extraction	06.10
1-fossil-fuel	3-oil-gas-extraction	06.10, 06.20
1-fossil-fuel	5-gas-distribution	35.22
2-utility	All	35.11, 35.12, 35.13, 36.00
2-utility	1-electricity-generation-fossil	35.11
2-utility	2-electricity-generation-renewable	35.11
2-utility	3-electricity-distribution	35.13
2-utility	4-utility-diversified	35.11, 35.12, 35.13, 36.00
3-energy-intensive	All	07.10, 20.16, 22.11
3-energy-intensive	1-category (e.g. cement, steel)	23.51, 24.10, 24.20, 20.15, 20.20
3-energy-intensive	2-category (e.g. plastic)	20.16, 20.17, 28.96, 22.11, 22.19
3-energy-intensive	3-category (e.g. non-fossil min.)	07.10, 08.91, 24.46, 28.13, 28.30
3-energy-intensive	4-category (e.g. electrical)	27.20, 27.33, 27.40, 27.31, 27.90
3-energy-intensive	5-category (e.g. food, other)	20.53, 20.59, 23.31, 25.73, 26.11
5-transportation	All	30.30, 42.11, 49.20
5-transportation	1-air-vehicles	30.30, 51.10, 51.21
5-transportation	1-air-infrastructure	30.30, 51.10, 51.21
5-transportation	2-road-vehicles	29.10, 29.31, 20.32
5-transportation	3-road-infrastructure	42.11, 42.13, 52.21
5-transportation	4-transportation-services	53.10
5-transportation	5-railways	30.20, 42.12, 49.10, 49.20

NOTES: Categories of transition risk and rules for weight rebalancing in the portfolio optimization. Within each CPRS Main sector, issuers are grouped in categories from 1 to 5, based on their CPRS2 sector, with decreasing levels of transition risk (i.e. category 5 has the lowest risk level). Example NACE 4 digits codes are reported in column 3. Within the sector utilities, issuers are grouped based also on technology information, not contained in the NACE codes (see text). The portfolio optimization performs weight transfers between pairs of issuers within the same CPRS Main and from a category with higher level of transition risk to a category with lower level of transition risk. Within transportation, air vehicles and infrastructure are in two different categories due to diversity of business model, but they are assigned the same level of transition risk. Additional rules may apply as indicated in the text.

- CPRS Main 05-transportation: issuers engaged in activities directly and indirectly related to transportation (e.g. vehicle manufacturing, infrastructures and services), grouped based on CPRS2 sector. In the sample, service transportation includes only post operators.

The portfolio transition risk measure is defined by the CPRS2 for fossil-fuels, transportation and energy-intensive; by a combination of CPRS2, CAPEX, and the NEF Index for utilities.

With CPRS2, we can take into account the technological profile of issuers and the relative climate transition risk within a given sector. For instance, the order in Exhibit 4 implies that a portfolio more skewed toward gas, rather than oil, is less exposed to climate transition risk. Hence, an investor willing to reduce their climate transition risk, while still maintaining a constant exposure at the CPRS Main level, can move weight from oil to gas in order to reduce it. Similarly, within transportation, an investor can move portfolio weight from air transportation to railways in order to reduce transition risk.

EXHIBIT 5

GHG Emissions across CPRS Main Sectors and Categories of Transition Risk

CPRS Main	Transition Risk Category	Average GHG Emission in Intensity	Average Total GHG Emissions	Issuers Count
1-fossil-fuel	All	1,725.42	115,320,277.47	28
1-fossil-fuel	1-coal-extraction	1,732.71	372,724,000.00	1
1-fossil-fuel	2-oil-extraction	2,571.04	245,344,888.89	12
1-fossil-fuel	3-oil-gas-extraction	6,271.06	145,946,960.00	2
1-fossil-fuel	5-gas-distribution	440.11	791,155.13	13
2-utility	All	1,633.44	52,740,822.66	46
2-utility	1-electricity-generation-fossil	2,849.22	117,820,506.33	12
2-utility	2-electricity-generation-renewable	1,481.85	32,657,609.67	6
2-utility	3-electricity-distribution	484.89	1,325,728.56	9
2-utility	4-utility-diversified	964.86	13,196,606.80	5
3-energy-intensive	All	1,229.82	33,180,251.43	69
3-energy-intensive	1-category (e.g. cement, steel)	1,836.59	56,323,136.14	17
3-energy-intensive	2-category (e.g. plastic)	1,638.01	67,290,800.00	7
3-energy-intensive	3-category (e.g. non-fossil min.)	1,224.54	3,500,000.00	1
3-energy-intensive	4-category (e.g. electrical)	1,090.67	25,280,935.08	14
3-energy-intensive	5-category (e.g. food, other)	807.88	15,557,342.81	30
5-transportation	All	1,031.81	84,926,792.91	51
5-transportation	1-air-vehicles	4,090.92	303,809,294.33	7
5-transportation	1-air-infrastructure	204.61	1,751,877.00	5
5-transportation	2-road-vehicles	629.61	140,129,223.80	13
5-transportation	3-road-infrastructure	263.67	8,313,552.43	16
5-transportation	4-transportation-services	295.54	19,375,666.67	3
5-transportation	5-railways	168.53	8,067,500.00	7

NOTE: Average total GHG emissions, GHG emission intensities and count of issuers grouped by categories of transition risk as defined in Exhibit 4.

SOURCE: authors' elaboration on Refinitiv EIKON data.

The measure for climate transition risk is ordinal in nature, and Exhibit 4 describes rankings within a given CPRS Main. In the following, we use a ranking from 1 to 5 to define exposure to transition risk, where 1 denotes the most exposed class and 5 the least exposed class.

Thus, we define a company as being less exposed to climate transition risk than another one if the integer of its transition risk category is higher.

The procedure for the portfolio rebalancing is tightly dependent on two factors: 1) the chosen measure of exposure to transition risk and 2) the definition of a company's business activity. In this study, the first one is addressed as defined in Exhibit 4,[21] while for the purpose of the second, only the main NACE 4-digit activity is considered. While there are clear limitations behind this approach—that is, that many companies have side activities whose impacts end up neglected—it allows us to show the possibility of a rebalancing within the boundaries of the weak market neutrality condition. A shift toward a definition of transition risk based on the portfolio of activities of a certain company shall be object of further research.

Importantly, there is a clear and negative relationship between the level number for transition risk categories defined in Exhibit 4 and GHG emission intensities for the corresponding transition risk levels as shown in Exhibit 5.

[21] Despite several approaches have been proposed to quantify climate transition risk, no consensus has been reached so far.

Climate-Aware Portfolio Rebalancing

The rebalancing algorithm to reduce a portfolio's climate transition risk proceeds iteratively. At each iteration, it increases the share of weight reallocated from corporate bonds that are more exposed to climate transition risk to bonds that are less exposed, while keeping constant the total exposure of the portfolio to each CPRS Main sector, the financial rating, and maturity profile of the portfolio, as consistent with Definition 2. Each bond is used only once; that is, its weight can be modified only once in the iteration. This means that bonds are paired for the purpose of the recalibration. The procedure is illustrated in Algorithm 1.

The portfolio reallocation algorithm works on CPRS1-fossil-fuel, CPRS2-utility|electricity, CPRS3-energy-intensive, CPRS5-transportation leaving out the remaining CRPS sectors. This is due to the lack of a consistent way to classify business activities in terms of their exposure to climate transition risk. It is also important to consider that, under weaker market neutrality, the ECB must keep the exposure constant by sector and country.[22] This imposes limitations as some countries do not have bonds that are eligible and are less exposed to climate transition risk. Hence, weights for those countries cannot be recalibrated. As a general rule, a rebalancing is possible only with respect to countries with a diversified bond universe.

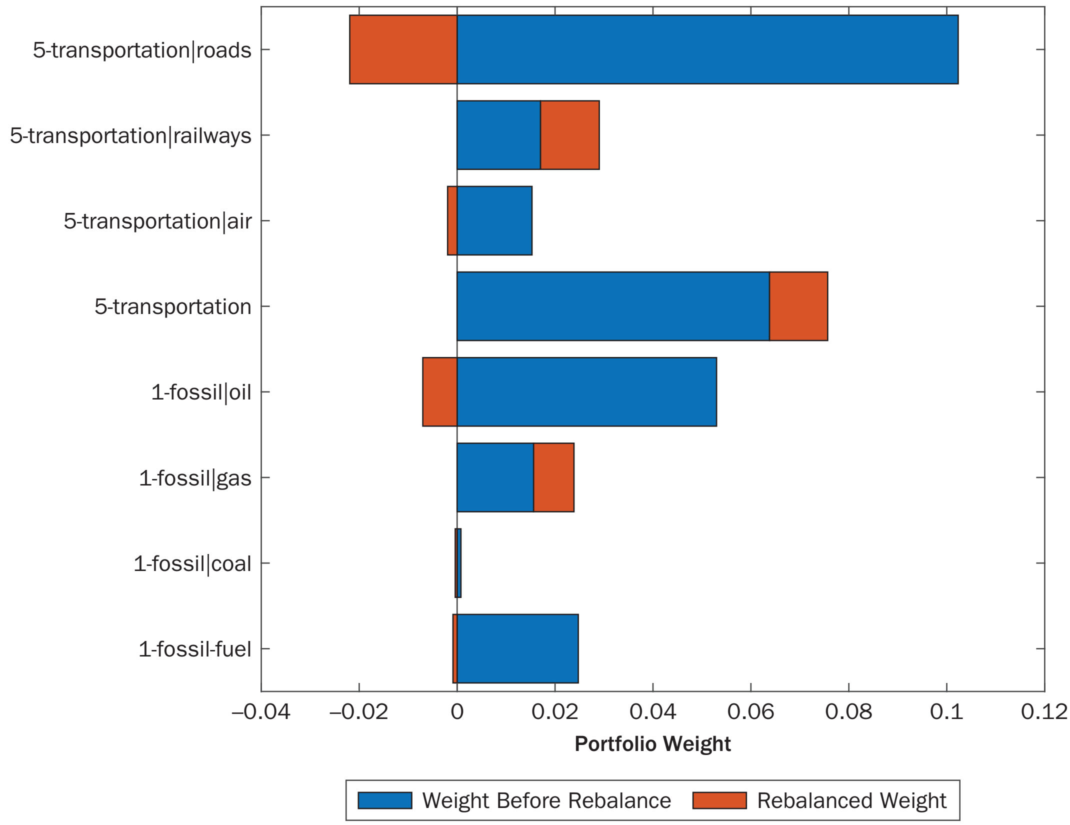
Algorithm 1: Portfolio reallocation algorithm, following the rules defined in Exhibit 4. The algorithm terminates when one of the following conditions occurs: 1) the rating profile worsen, 2) the maturity profile differs significantly from the original, 3) the maximum share of weight (0.5) is moved for all bonds.

```
Result: New portfolio allocation with reduced transition risk
initialization; while Rating profile constant, Maturity profile constant, and ω > 1 do
 ω = 5; for Country in Country List do
  for CPRS Main in CPRS Main list do
   Select all bonds in CPRS Main
   if CPRS Main == "1-fossil-fuel" or CPRS Main == "5-transport" then
    Select all bonds more exposed to transition risk in the given CPRS Main, according to the transition risk category;
    Pair each more exposed bond to a less exposed one in the same CPRS Main;
    Move weight constant 1/ω from more exposed to less exposed bond;
   else if CPRS Main == "2-utilities" then
    Select all bonds more exposed to transition risk in the given CPRS Main, according to the transition risk category described above
    Pair each more exposed bond to a less exposed one in the same CPRS Main;
    Move weight constant 1/ω from more exposed to less exposed bond;
   else if CPRS Main == "3-energy-intensive" then
    Select all bonds more exposed to transition risk in the given CPRS Main, according to the transition risk category defined by the
    CPRS2 classification
    Pair each more exposed bond to a less exposed one in the same CPRS Main;
    Move weight constant 1/ω from more exposed to less exposed bond;
   else
    Do not rebalance;
   end
  end
 end
 if All criteria are still satisfied then
  Decrease ω and repeat
 else
  Keep last rebalanced weights set;
 end
end
```

[22] This constraint is relaxed in the second part of the simulation study.

EXHIBIT 6

Portfolio Weights Rebalancing, CPRS1-Fossil-Fuel and CPRS5-Transportation



NOTES: Blue bars represent total weight for a given CPRS2 before the portfolio rebalance, while red bars represent the portfolio weight moved away, or toward, a given CPRS2. In CPRS1-fossil-fuel, weight is moved from oil producers, or producers of both oil and gas, toward gas distributors; in CPRS5-transportation, weight is moved away from car manufacturers and airlines or airport operators toward infrastructures and railways. For a detailed discussion of the order of transition risk categories, please refer to Exhibit 4.

SOURCE: Data on portfolio composition sourced from the ECB, as elaborated by the authors.

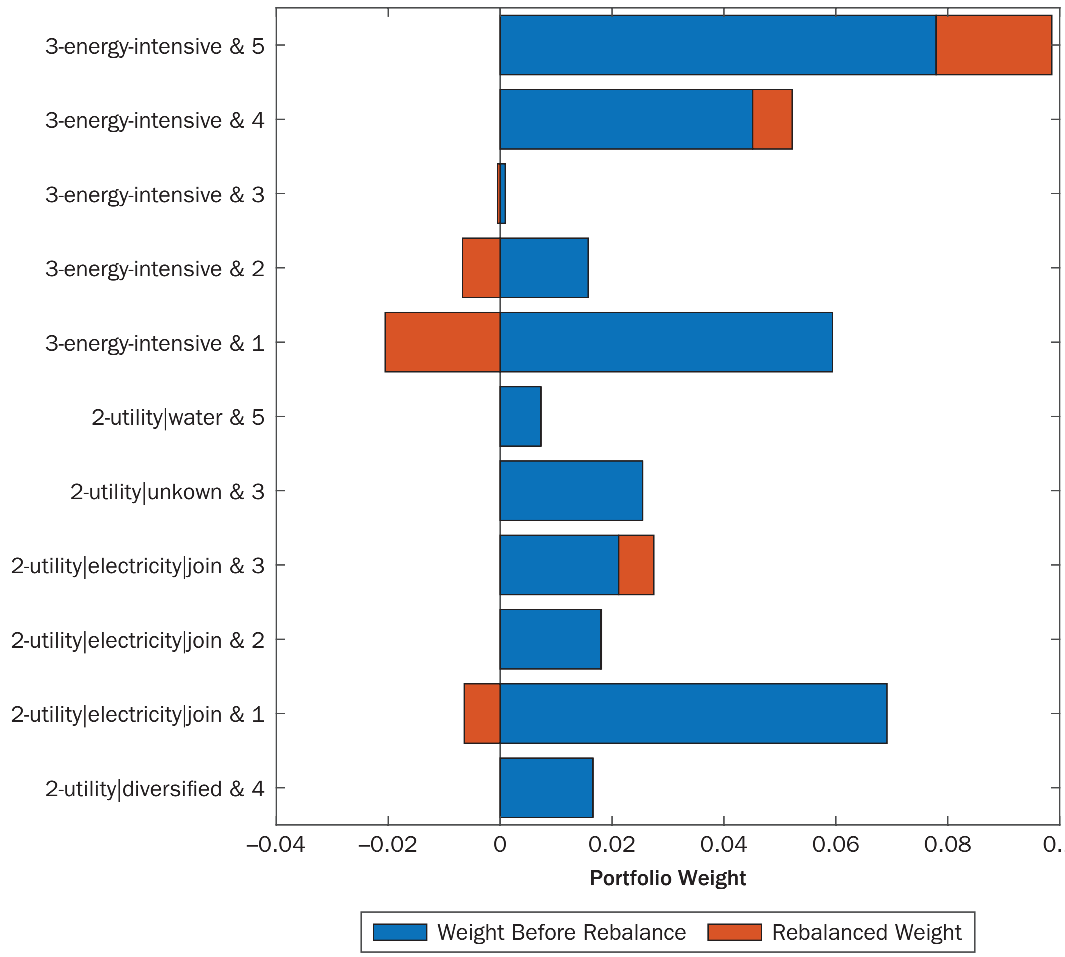
Note that this exercise has been performed considering the initial allocation of funds in the ECB portfolio. Thus, the alternative portfolio represents a possible different allocation as of November 6, 2020. In the last part of our simulation, we present estimates of market impact for the rebalancing, under a simplified setting.

The algorithm is run until the maximum weight (half of original in the first part implementation) for exposed bonds is shifted, with roughly constant maturity and rating profiles (average rating improves from 7.20 to 7.14, while average maturity slightly increases from 5.99 to 6.00). Out of 1,588 bonds, 408 experience a positive or negative weight change. Because bond weights can be adjusted only once, this means that weight is moved from 204 bonds more exposed to climate transition risk to 204 bonds with reduced climate transition risk. In terms of issuers, the impact is on 98 unique issuers, out of 332 in the portfolio.

The results of the rebalancing are shown in Exhibit 6 for CPRS1-fossil-fuel and CPRS5-transportation and in Exhibit 7 for CPRS2-utility|electricity and CPRS3-energy-intensive. The first part of the rebalancing is run using the CPRS2 classification as a metric of exposure to climate transition risk, while the second part is run using the CPRS2 for energy intensive, and the combination of the NEF Index, renewable capacity, and CAPEX greenness for utilities.

EXHIBIT 7

Portfolio Weights Rebalancing, CPRS2-Utility|Electricity and CPRS3-Energy-Intensive



NOTES: Blue bars represent total weight for a given CPRS2 before the portfolio rebalancing, while red bars represent the portfolio weight moved away, or toward, a given CPRS2. After each CPRS2, a value from 1 to 5 is reported indicating the computed transition risk category. Higher numbers represent companies less exposed to transition risk. For utilities, a CPRS in the picture is denoted as "2-utility|electricity|join": it represents a combination of companies in the CPRS "2-utility|electricity|generation," "2-utility|generation|-transmission," "2-utility|electricity|distribution," and "2-utility|electricity|trade." For a detailed discussion of the order of transition risk categories, please refer to Exhibit 4.

SOURCE: Data on portfolio composition sourced from the ECB, as elaborated by the authors.

We can conclude from the exhibits that the existing market structure offers limited potential for rebalancing under market neutrality. Nevertheless, it is still possible to move weights away from "high carbon" to "green" activities, for example, from air transport to railways. The manufacturing sector offers a relatively larger leeway due to the higher number of companies that are less exposed to transition risk. In contrast, utilities have a lower leeway due to the country constraint.

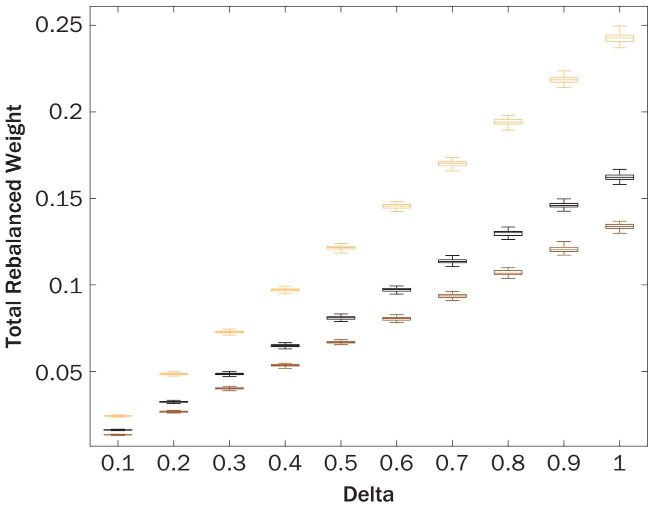
Our exercise, while conservative, shows that it is possible to rebalance the portfolio of an investor—here, the ECB—to achieve a lower exposure to climate transition risk under weaker market neutrality.

We also investigate the performance of the algorithm under more relaxed conditions. Two parameters can be adjusted: 1) the share of weight moved from a more exposed to a less exposed bond and 2) the stringency of the geographical constraint.

Starting from the latter, we propose three simulation rounds considering gradually relaxed country allocation constraints. In the first setting, which follows the same

EXHIBIT 8

Portfolio Weights Rebalancing, All CPRS, Conditioned to Different Country Constraints



NOTES: Black boxes: country allocation constrained by country of domicile. Brown boxes: country allocation constrained by national bank performing the purchases. Yellow boxes: no country constraints. Each box represents the variability of 100 simulated portfolios, which are run with the corresponding level of country constraints and a weight-moved delta starting at 0.1 at the horizontal axis. To simulate different portfolios, a random shuffling is used in the pairing of bonds. Horizontal axis: delta representing the weight moved from more exposed to less exposed bond. Vertical axis: total rebalanced weight in the portfolio.

SOURCE: Authors' elaboration on ECB portfolio data.

country constraints as previously and is aligned with Definition 2, we consider a constant country allocation by domicile of the issuer. In the second setting, we consider a constant country allocation by a national central bank performing the purchases. In the third setting, we leave the country composition unconstrained, that is, we allow it to change freely. Under each configuration, the weight moved δ varies from 0.1 to 1. The results are shown in Exhibit 8. For the purpose of the simulation, 100 portfolios are run for each level of stringency of country constraints, with delta varying from 0 to 0.1, 0.2, …, 1.

The simulation study confirms our expectations about the impact of relaxed constraints and increased delta. Both lead to larger rebalances. Importantly, for low values of delta, there is limited leeway to perform any rebalance. Furthermore, the total weight moved under a given combination of constraints and delta is similar across portfolios. Overall, the analysis confirms that the ECB faces significant limitations in its actions stemming from the market structure.

Market Impact of Climate Portfolio Rebalancing

Complementing the simulation analysis, we add a measure of the market impact of the portfolio rebalancing. We adopt a "naive" approach by building on the literature. Specifically, Abidi and Miquel-Flores (2018) identify two levels of announcement effect within the CSPP: for bonds above the BBB– "market cutoff" to define investment-grade bonds, a 5 basis point (bp) yield compression, while for bonds below the "market cutoff" but still eligible under the CSPP, a 15 bp yield compression. According to the authors, the existence of this discontinuity is caused by the "best of" approach to issuer ratings of the ECB. Indeed, while the ECB considers the best rating across major agencies for purpose of eligibility (i.e., a single investment grade is sufficient to include a bond in the CSPP), the market generally does not. This implies that some high-yield bonds will be eligible under the CSPP and hence undergo a stronger yield compression. We reproduce this rule by assigning a baseline announcement effect of + (–) 5 bp for bonds that are sold (bought) within the rebalancing and are above the BBB– market threshold and assigning a baseline announcement effect of + (–) 15 bp for bonds that are sold (bought) within the rebalancing and are below the BBB– market threshold.

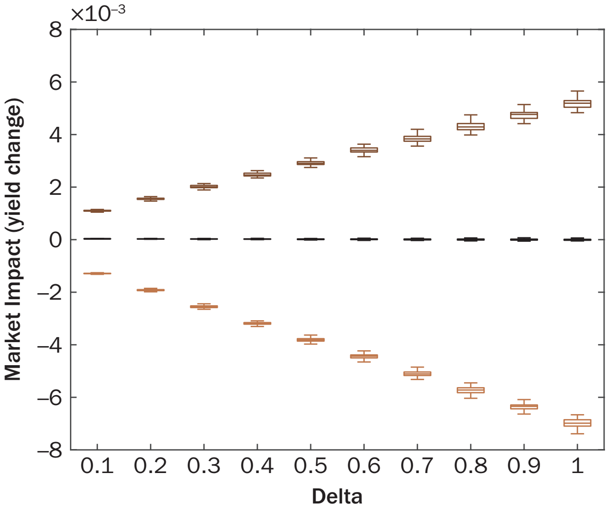
Other studies have focused on the impacts of the quantitative easing (QE), together with its spillover effects on bond issuance and bond-loan substitutions. Estimates of impact of the CSPP vary (see Arce, Mayordomo, and Gimeno 2020; Grosse-Rueschkamp, Steffen, and Streitz 2019; Todorov 2020).

In this article, we consider the discontinuity approach (Abidi and Miquel-Flores 2018) in light of 1) the use of the largest CSPP-eligible sample in the literature and 2) the relevance of the discontinuity approach in our optimization setting.[23]

[23] With the rating constraint from the ECB, the difference in the announcement effect is of particular importance. In this sense, a redistribution from bonds with higher ratings to bonds with lower ratings would increase market impact significantly.

EXHIBIT 9

Market Impact of Portfolio Weight Rebalancing for Varying Levels of the Moved Weight *Delta*



NOTES: Box plot of market impact as a function of moved weight, Delta, in the rebalancing. Black boxes: series of average yield movements in the whole sample. Brown boxes: series of positive yield movements (i.e., increase in yield after sales). Yellow boxes: series of negative yield movements (i.e., compression in yield after purchases). Each box represents the 25–75 percentile range for the specific metric (net effect, positive effect, negative effect) over a set of 100 random portfolios. To simulate different portfolios, a random shuffling is used in the pairing of bonds. Horizontal axis: delta representing the weight moved from more exposed to less exposed bond. Vertical axis: market impact, calculated as change in yield for a given bond, expressed as a pure number. A value of 0.01 represents a change in weight of 0.01, that is, 1% or 100 basis points.

SOURCE: Authors' elaboration on ECB portfolio data.

In addition to the announcement effect, we consider a size effect: the larger the size of the sales for a given issuer, the larger the impact on its bonds. To simplify, we assume that this change is transmitted directly to yields, over the baseline; that is, $\Delta(yield) = Baseline + \Delta(purchasevolume)$. This is consistent with the idea that larger purchases or sales have larger impact. This enables us to understand the impact of the rebalancing.[24]

The results are shown in Exhibit 9. We find a limited effect,[25] which ranges between –80 and 80 bp.

We must consider two things. First, despite the average impacts being constrained, a maximum impact can be significant. Second, there is a general tendency toward a yield compression effect, as shown by the average (black) boxes being slightly below zero as δ approaches 1. This could be due either to a larger share of less exposed bonds close to the market threshold or to a larger impact of the rebalancing, as a result of the lower amount of debt originated by less exposed companies.

Greenness Confusion and Greenwashing

It is now important to understand how the transition risk measure defined in this article relates to other ones generally used by practitioners or in the literature (in this study, science-based targets, ESG score, and GHG emissions). A preliminary analysis of the relationship between them is depicted in Exhibit 10, which shows the cross-correlations in the dataset at the issuer level. Note that the sample size is constrained by two factors: the transition risk measure, which is defined only for selected CPRS; and Scope 3 emissions, which are available only for a subset of issuers.

Exhibit 10 shows that correlations are negative for GHG emissions and ESG scores, indicating that companies that have more GHG emissions or a higher ESG risk are associated with higher transition risk. In contrast, signs are positive for science-based targets, indicating that companies with more ambitious targets are associated with lower transition risk. Correlations confirm that the relationship between the measure underlying the rebalance and alternative ones, such as GHG emissions, moves in the expected direction.

A further exploration of this result requires us first to discuss the relationship between the measure of transition risk defined to support a weaker market neutrality and Scope 3 emissions. As mentioned, the reliability of Scope 3 data is limited. This is confirmed by our sample, where deep dives in GHG emissions data show significant inconsistencies. Exhibit 11 further elaborates on the example from the automotive sector, considering also Daimler AG and BMW AG. It also adds a comparison of utility companies with different shares of renewable generation capacity.

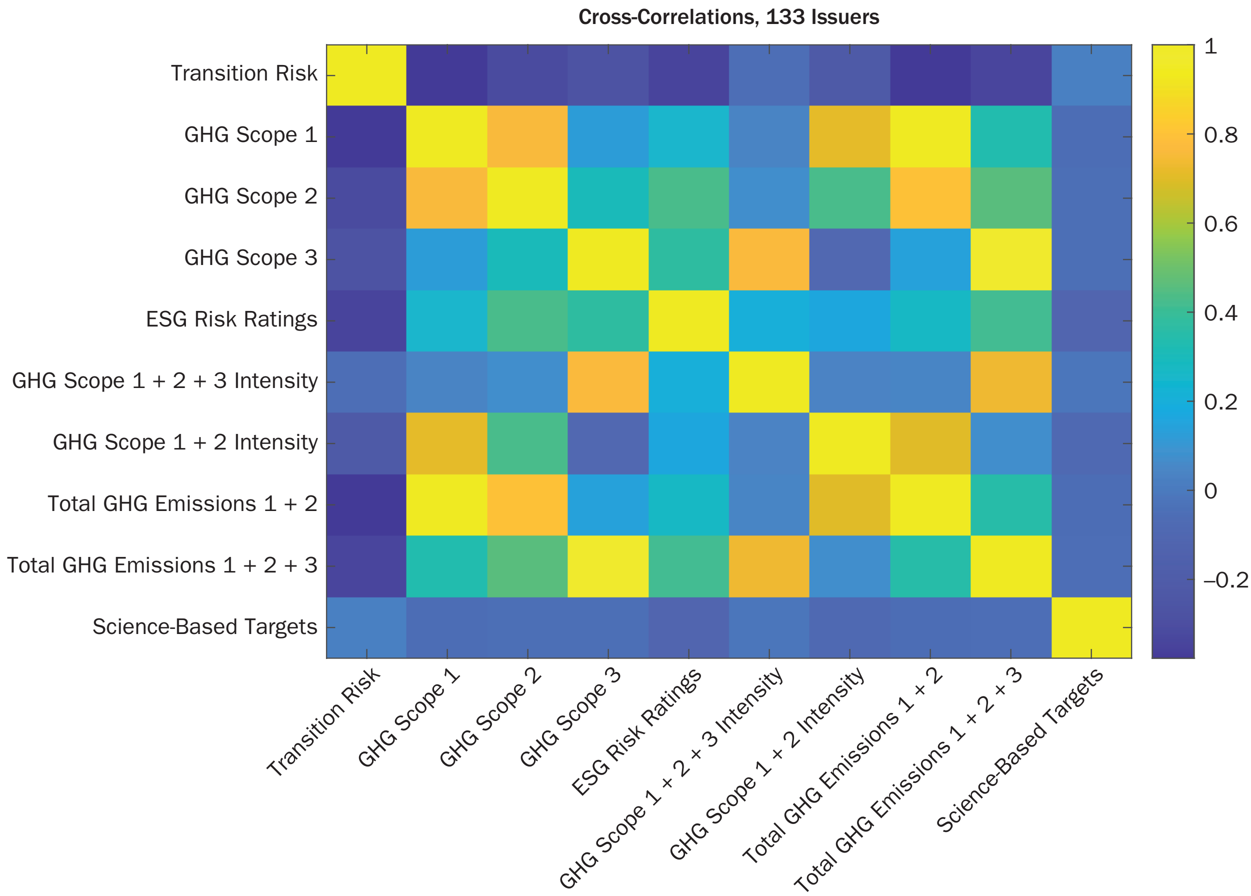
While Exhibit 11 illustrates a subset of issuers, the problems are endemic and accumulate over the share of missing Scope 3 data. There are significant reporting

[24] This assumption can be further refined or supported by additional empirical analysis.

[25] Note that for the purpose of this exercise, only the domicile-based version of weak neutrality is considered—that is, the potential for rebalancing is highly constrained.

EXHIBIT 10

Cross-Correlations across Variables in the Dataset, for 133 Issuers



NOTES: For the transition risk measure, correlation with GHG emissions varies between a minimum of –0.37681 (with total GHG emissions 1 + 2) and a maximum of –0.05316 (with Scope 1 + 2 + 3 intensity). The correlation is weakly positive (0.02793) with the strength of science-based targets and negative (–0.33966) with the ESG scores.

SOURCE: Authors' elaboration on the data presented in Exhibit 3.

inconsistencies at the issuer level that cannot be ignored in empirical analyses. In the case of automakers, despite the relatively consistent average fleet emissions, we see clear discrepancies in the calculated intensity that varies by a factor ranging from 2.5 to 40. In the case of generating utilities, we see a similar issue with companies having comparable generation capacity from renewable energy but GHG emission intensities differing of a factor of between 2 and 4.

Thus, if we proxy the transition risk of a company by its GHG emissions, and we perform the rebalancing by relying only on GHG emissions disclosed, we would minimize the GHG emission profile of the portfolio. The result would not reflect a viable economy and depart completely from any definition of neutrality. This is clearly illustrated by utilities in Exhibit 12. Shifting weight from electricity generation to transmission reduces GHG emission intensity. Nevertheless, it also implies a skew within the ECB's portfolio toward an unrealistic structure of the economy where generation plays a minor role. Hence, using GHG emissions only for rebalancing is not a viable strategy for a central bank. Exhibit 12 also shows the issues related to differences in reporting, due to the significant variability of intensities.

The discussed limitations of Scope 3 emissions, in the end, make the case for using the transition risk measure that we introduced in this article. Our measure

EXHIBIT 11

Selected Comparisons, CPRS 5-Transport|Roads and 2-Utility|Electricity|Generation

Consistency between Scope 3 Emissions Intensity and Business Models

Issuer	Indirect Renewable Capacity	Scope 1 + 2 + 3 Emission Intensity
A2A S.p.A.	21%	1,086.31
Engie S.A.	41%	2,708.13
ENEL S.p.A.	49%	2,167.92
Fortum Oyj, Helsinki	52%	4,099.53
Iberdrola SA	66%	1,697.08
ERG S.p.A	67%	1,387.26
Verbund AG	69%	436.37
EDP—Energias de Portugal SA	76%	1,836.66
Issuer	**Average Fleet Emissions**	**Scope 1 + 2 +3 Emission Intensity**
Bayerische Motoren Werke AG	127.00	650.47
Daimler AG	137.00	424.92
FCA NV (Stellantis NV)	124.80	40.47
Volkswagen AG	124.00	1,607.27

NOTES: This exhibit shows differences in reporting for Scope 1 + 2 + 3 emission intensity against fundamentals that should be related to it. Upper panel: comparison of indirect renewable energy capacity (in %) and Scope 1 + 2 + 3 emission intensity (in tonnes/USD million) for different issuers. Lower panel: comparison of average fleet emissions (in g/km) and Scope 1 + 2 + 3 emission intensity (in tonnes/USD million). For automakers, average fleet emissions are sourced from Refinitiv. For generation utilities, total renewable capacity is elaborated from the authors based on company disclosures. Data are for the year 2019.

proves to be less noisy and supports the reduction of transition risk.

We further justify the case for using the proposed measure by answering two questions:

- Do the rebalanced portfolios have lower GHG emissions?
- How does the rebalancing interact with such other measures of transition risk as GHG emissions, ESG scores, green bonds, and science-based targets?

Exhibit 13 illustrates the relationship between the GHG emission intensity of 10,000 simulated portfolios and the respective amount of rebalanced weight. A clear negative relationship between the two variables emerges, implying that lower GHG emission intensities correspond to higher rebalancing or, rephrasing, that the greater the rebalanced portion of the portfolio, the lower its carbon intensity.

Then, we investigate the effects of the rebalancing and its relation to GHG emissions, ESG scores, green bonds, and carbon neutrality targets via an ordered logistic regression. We first simulate 500 portfolios and average the weight moved from or to bonds across all scenarios. We restrict the sample to the bonds for which the transition risk measure is defined.[26] We estimate the likelihood of a bond being bought or sold during the rebalancing. Our target variables are binary, with the variable *BondSold* taking a value of 1 if the bond is sold on average, and 0 otherwise, and the variable *BondBought* taking a value of 1 if the bond if bought on average, and 0 otherwise. We estimate the following logistic regressions for bought and sold bonds:

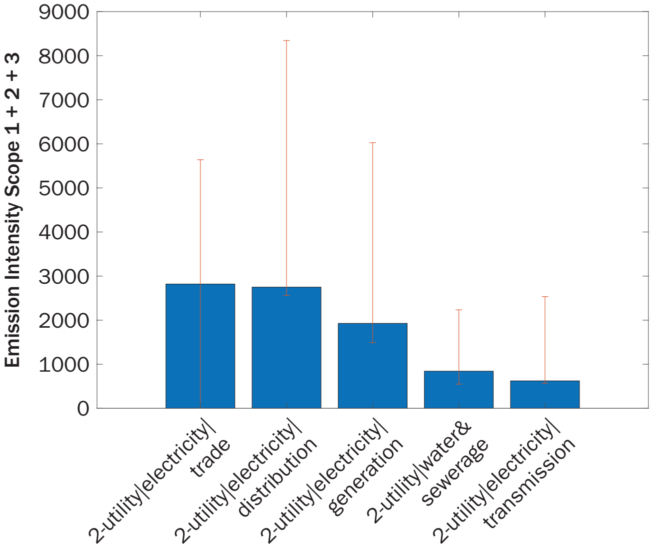
$$\begin{aligned} BondBought_i = {} & \beta_0 + \beta_1 BondMaturity_i + \beta_2 BondCouponRate_i + \beta_3 GreenBondFlag_i \\ & + \beta_4 BondAmountOutstanding_i + \beta_5 IssuerBestRating_i \\ & + \beta_6 IssuerRevenue_i + \beta_7 ScienceBasedTargetsStrength_i \\ & + \beta_8 IssuerESGRiskRating_i + \beta_9 IssuerScope123Emissions_i + \varepsilon_i \end{aligned} \quad (1)$$

$$\begin{aligned} BondBought_i = {} & \beta_0 + \beta_1 BondMaturity_i + \beta_2 BondCouponRate_i + \beta_3 GreenBondFlag_i \\ & + \beta_4 BondAmountOutstanding_i + \beta_5 IssuerBestRating_i + \beta_6 IssuerRevenue_i \\ & + \beta_7 ScienceBasedTargetsStrength_i + \beta_8 IssuerESGRiskRating_i \\ & + \beta_9 IssuerScope123EmissionsIntensity_i + \varepsilon_i \end{aligned} \quad (2)$$

[26]Restricting the sample could be seen as a bias for the analysis. We acknowledge this consideration and contextualize our results with respect to CPRS where the transition risk measure is defined. This said, we do not see this restriction as a major concern because the measure is defined for those sectors that are most relevant for climate policy.

EXHIBIT 12

Average Scope 1 + 2 + 3 Emission Intensities within CPRS2, Including Max-Min Error Bars



NOTES: Horizontal axis: selected CPRS2 representing the Utilities sector. Vertical axis: GHG emission intensity including Scope 1, 2 and 3, expressed in $tCO2e$/USD million.

SOURCE: Authors' elaboration on Eikon data.

where

- *BondBought$_i$* is the categorical target variable described above, to be replaced in the equations with *BondSold$_i$* for the case of bought sold.
- *BondMaturity* represents the maturity in years.
- *BondCouponRate* its coupon in percentage (we exclude floaters from the regression).
- *GreenBondFlag* is a binary variable describing whether the bond is a green bond or not.
- *BondAmountOutstanding* is the total amount outstanding in euros as of November 2020.
- *IssuerBestRating* is the best issuer or issue rating as described earlier.
- *IssuerRevenue* its revenue for fiscal year 2019 in US dollars.
- *Science-BasedTargetsStrength* represents the categorical strength assigned to the decarbonization targets, as described.
- *IssuerESGRiskRating* is the ESG risk of the issuer as provided by Sustainalytics.
- *IssuerScope*123*Emissions* is the total Scope 1 + 2 + 3 emissions in tons.
- *IssuerScope*123*EmissionsIntensity* is the total Scope 1 + 2 + 3 emission intensity in $tCO2e$/USD million.
- ε_i is the stochastic error.

The results are presented in Exhibit 14 and are influenced by the issuer-level data limitations described earlier.[27] First, we notice that bonds with a higher (lower) ESG risk rating are more likely to be sold (bought) in all specifications of the model. Indeed, the coefficient is negative and significant for bought bonds in both specifications of the model, and positive and significant for sold bonds. Effects of targets or green bonds are not clear, with green bonds label being associated with lower likelihood of bonds being bought or sold. Moreover, targets are negatively related to bought bonds. These results can be explained as follows. Considered that many fossil-fuel companies have GHG emission reduction targets, and issue green bonds for specific projects. Yet, they remain exposed to transition risk as their main sources of revenues are fossil fuels.

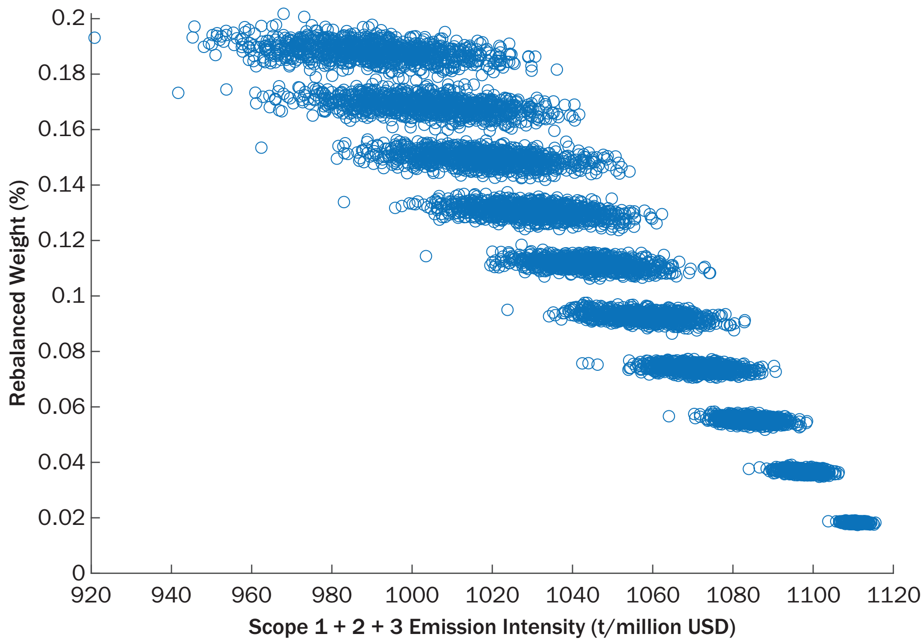
Finally, GHG emission variables offer mixed insights. Emission intensity is not significant for both the buy and sell versions of the model. Similarly, total GHG emissions are not significant for the sell version but are significant for the buy version. Bonds from issuers with higher total emissions are less likely to be bought.

Thus in order to perform a climate-aware portfolio rebalancing, one cannot solely rely on GHG emissions indicators. While our results should be considered in the light of the criticality of Scope 3 reported data, they confirm the need for investors and financial authorities to use complementary measures, such as the transition risk measure that we developed in this article.

[27] We acknowledge that the regression is run at the bond level. This implies that issuers with more bonds are naturally more weighted for the results.

EXHIBIT 13

Scope 1 + 2 + 3 Emissions Intensity and Corresponding Share of Rebalanced Weight, over 10,000 Simulated Portfolios



NOTES: The relationship between carbon intensity and the rebalanced weight is negative. The larger the rebalancing, the larger the GHG emissions reductions. Horizontal axis: Scope 1 + 2 + 3 emission intensity, in tCO_2e/USD million. Vertical axis: Percentage of rebalanced weight in the portfolio.

SOURCE: Authors' elaboration on Eikon data.

EXHIBIT 14

Issuer Level Logistic Regression for Bonds Sold and Bought in the Rebalancing

Variables	(1) BondSold		(2) BondBought		(3) BondSold		(4) BondBought	
BondMaturity	–0.0528*	(–2.23)	–0.00570	(–0.22)	–0.0530*	(–2.26)	–0.0113	(–0.42)
BondCouponRate	–0.103	(–1.40)	–0.0974	(–1.22)	–0.106	(–1.47)	–0.132	(–1.62)
GreenBFlag	–0.989*	(–2.33)	–2.083**	(–2.67)	–0.995*	(–2.36)	–2.691**	(–2.94)
AmountOutstanding	9.59e-10***	(3.40)	–1.93e-10	(–0.56)	9.26e-10**	(3.29)	–6.63e-11	(–0.19)
IssuerBestRating	0.182***	(4.31)	–0.342***	(–5.77)	0.179***	(4.24)	–0.413***	(–6.36)
ScienceBasedTargets	0.0177	(0.53)	–0.221***	(–4.32)	0.0128	(0.38)	–0.222***	(–4.25)
IssuerRevenue	6.43e-12**	(3.01)	–1.66e-11***	(–4.32)	6.65e-12***	(3.39)	–2.36e-11***	(–6.84)
IssuerESGRiskRating	0.0592***	(4.57)	–0.0419*	(–2.27)	0.0614***	(4.72)	–0.0599**	(–2.87)
Scope123Emissions	4.42e-10	(0.65)	–5.66e-09**	(–2.65)				
Scope123Intensity					0.0000609	(1.32)	0.0000118	(0.19)
_cons	–4.057***	(–7.58)	3.765***	(5.21)	–4.099***	(–7.70)	4.613***	(5.92)
N	778		778		771		771	

NOTES: Models (1) and (2) estimate Equation 1 for sold and bought bonds respectively. Models (3) and (4) estimate Equation 2 for sold and bought bonds respectively. t-Statistics are presented in parentheses next to the estimates. p-Values are presented next to the estimate under the following convention: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$. Results are elaborated by the authors using Stata (StataCorp 2021). Explanatory variables: *BondMaturity* represents the maturity in years. *BondCouponRate* the coupon in percentage. *GreenBFlag* is a binary variable describing whether the bond is a green bond or not. *AmountOutstanding* is the total amount outstanding in euros as of November 2020. *IssuerBestRating* is the best issuer or issue rating. *ScienceBasedTargets* represents the categorical strength assigned to the science-based targets. *IssuerRevenue* its revenue for fiscal year 2019 in USD. *IssuerESGRiskRating* is the ESG risk of the issuer as provided by Sustainalytics. *Scope123Emissions* is the total Scope 1 + 2 + 3 emissions in tons. *Scope123EmissionsIntensity* is the total Scope 1 + 2 + 3 emission intensity in tCO_2e/USD million. *cons* is the constant.

CONCLUSIONS

In this article, we have developed an approach that allows investors, including central banks, to rebalance their portfolios of corporate bonds in order to decrease their exposure to climate transition risk. We showed how a portfolio of corporate bonds can be rebalanced, with a climate tilting, shifting weights away from issuers that are more exposed to climate transition risk to issuers that are less exposed, while respecting a set of sustainability and investment criteria.

To do so, we introduced a measure of transition risk that allows us to overcome the limitations of GHG emissions reporting and ESG scores.

While the approach is applicable to all investors, we have focused our analysis on the ECB's corporate bond purchases. Thus, we considered a rebalance constrained by the so-called market neutrality principle, which has been followed by the ECB and other central banks.

We demonstrated analytically that under a strict market neutrality principle, the ECB's corporate bond portfolio is completely determined and there is no room for rebalancing it to lower the exposure to climate transition risk. Thus, if markets do not fully price transition risks, the ECB cannot reconcile market neutrality with climate change considerations.

We then defined a weaker market neutrality principle and show that it is now possible to rebalance the portfolio. The weaker principle is grounded in the CPRS classification of economic activities and focuses on their technological profiles.

We developed an algorithm to perform the rebalance and achieve a reduction in transition risk despite the limited leeway for the ECB. We also studied the market impact of the rebalance, finding that average market impact for the set of bonds in the portfolio would be negligible and impact on individual bonds would be up to 80 bp.

Finally, we discussed the relationship between the measure of transition risk that we defined with other measures of transition risk, in particular with GHG emissions, ESG scores, green bonds, and science-based targets. Importantly, we highlighted the main limitations in Scope 3 emission data. Our results make the case for using alternative measures for climate-aware portfolio rebalancing.

Despite the discussed limitations, we showed how the ECB, or a general investor, can rebalance the corporate bond portfolios using the proposed algorithm. In particular, we find that bonds issued by firms with lower (higher) ESG risk are more likely to be bought (sold) in the rebalancing, while bonds issued by firms with higher GHG emissions are less likely to be bought.

APPENDIX

PROOFS OF PROPOSITIONS

Proof of Proposition 1

We consider an economy of $n \in \mathcal{N}$ companies, indexed by j. Each company is assigned to one sector S, indexed by $s \in S$, depending on its main business activity. The sectors S can be grouped in macro sectors MS, indexed by $m \in M$. Companies finance their activities via bonds, and the full universe of bonds is denoted as $\mathcal{B}$, where each element $b_{i,j} \in \mathcal{B}$ represents bond i for company j.

The climate transition risk for each sector is defined as Q_s. While it is not possible to define a global ordering of Q across all sectors, it is possible to determine a local ordering of Q within a certain macro sector MS; that is, it is possible to write:

$$\text{For } S_1,\ldots,S_{k_1} \in MS_1 : Q_{S_1} < Q_{S_2} < \ldots < Q_{S_{k_1}}, \tag{A1a}$$

$$\text{For } S_{k_1+1},\ldots,S_{k_2} \in MS_2 : Q_{S_{k_1+1}} < \ldots < Q_{S_{k_2}}, \tag{A1b}$$

$$\ldots, \tag{A1c}$$

$$\text{For } S_{k_h+1},\ldots,S_S \in MS_M : Q_{S_{k_h+1}} < \ldots < Q_{S_S}. \tag{A1d}$$

where k_1, k_2, represent the indices for the last sector $S_s \in MS_1$, $S_s \in MS_2$, and so on.

For the bond markets, it holds:

$$S_{U_s} = \sum_{i \in \{b_i \in S\}} b_i \tag{A2}$$

and

$$S_{s,count} = \sum \mathbb{1}_{\{n_j \in S_s\}} \tag{A3}$$

where S_{U_s} represents the total amount outstanding in the bond market for sector s, and $S_{s,count}$ represents the number of issuers for sector s. We can define the sectorial structure of the universe portfolio as

$$S_U = [S_{U_1}; S_{U_2}; \ldots; S_{U_S}]. \tag{A4}$$

Clearly, this portfolio will be characterized by a certain climate transition risk Q_U defined as follows:

$$Q_U = \sum_{s \in S} \frac{S_{U_s}}{\sum_s S_{U_s}} Q_{S_s}. \tag{A5}$$

The investor's portfolio has a total known amount D to be invested in the market according to criteria 1–9. While criteria 1–6 determine the eligible universe, criteria 7–9 determine the weight limits and principles of the allocation. We can say that the total amount to be invested will be allocated according to a certain set of weights w_i satisfying

$$w_i = \frac{x_i}{D} \tag{A6}$$

where x_i represents the position (amount invested) in a given bond i and w_i is the corresponding weight in the portfolio—which we know is capped by a certain parameter α according to criterium 9. Clearly, it holds that $\sum_i w_i = 1$ and $\sum_i x_i = D$.

As for the market, the sector distribution of the portfolio can be defined as S_D

$$S_{D_s} = \sum_{j \in 1_{\{n_j \in S\}}} w_j D, \tag{A7}$$

leading to the following vector of sector level exposures:

$$S_D = [S_{D_1}; S_{D_2}; \ldots; S_{D_S}]. \tag{A8}$$

The strong market neutrality hypothesis as described in Proposition 1 implies purchases proportional to a certain benchmark, whose composition is determined by market capitalization; that is,

$$w_j = \frac{b_j}{\sum_j b_j} \tag{A9}$$

where the numerator captures all bonds issued by a certain company in the market, and the denominator captures all bonds in the market. We now want to show that, following this rule, a proportional relationship between S_D and S_U is implied, hence proving the proposition.

First, we substitute w_j in Equation (A7) following the proportionality as in Equation (A9) to obtain

$$S_{D_s} = \sum_{\{j \in s\}} \frac{b_j}{\sum_j b_j} D$$

where D and $\sum_j b_j = B$ are independent on the sector and can hence be taken out of the equation to obtain

$$S_{D_s} = \frac{D}{B} \sum_{\{j \in s\}} b_j \tag{A10}$$

where the last term in the equation is exactly S_{U_s}, implying a proportional relationship that cannot be avoided as long as Equation (A9) holds.

Moreover, it follows also from the definition in Equation (A5) that $Q_D = Q_U$; that is, the investor cannot influence her climate transition risk profile.

Proof of Proposition 2

We move in the same economy and bond market described in the proof of Proposition 1: We suppose Equations (A1) to (A8) still hold. For the definition of weak market neutrality, Equation (A9) does not hold anymore as the purchases are not proportional to issuers but rather to macro sectors, which were initially defined as *MS*. Hence, we first define components of MS_U and MS_D in terms of the sectors:

$$MS_{D_m} = \sum_{s \in m} S_{D_s}, \tag{A11a}$$

$$MS_{U_m} = \sum_{s \in m} S_{U_s}. \tag{A11b}$$

This yields to the following vector definitions for MS_D and MS_U:

$$MS_D = [MS_{D_1}; MS_{D_2}; \dots; MS_{D_M}], \tag{A12a}$$

$$MS_U = [MS_{U_1}; MS_{U_2}; \dots; MS_{U_M}]. \tag{A12b}$$

Following the definition of weak market neutrality, we know the following equation holds for the macro sector level, replacing Equation (A10):

$$MS_{D_m} = \frac{D}{B} MS_{U_m}, \tag{A13}$$

and by expressing the macro sectors in terms of their components, we obtain

$$MS_{D_m} = \sum_{j\in m} w_j D, \quad \text{(A14)}$$

$$MS_{U_m} = \sum_{j\in m} b_j \quad \text{(A15)}$$

By substituting, we obtain

$$\sum_{j\in m} w_j D = \frac{D}{B}\sum_{j\in m} b_j. \quad \text{(A16)}$$

Implying that weights w_j are now free to move, as long as the total weight allocated to a certain macro sector is constant. This implies that the investor can change its allocation across sectors and hence across issuers, without necessarily mimicking the exact structure of the market benchmark but just its macro sectoral composition—hence, yielding the proof.

Moreover, it is possible to find a portfolio that has less climate transition risk, that is, for which it holds $Q_D < Q_M$. Indeed, given Equations (A1a)–(A1d), it is possible to achieve a weight combination under which it simultaneously holds

$$Q_{MS_{1,D}} < Q_{MS_{1,M}} \quad \text{(A17a)}$$

$$\ldots \quad \text{(A17b)}$$

$$Q_{MS_{N,D}} < Q_{MS_{N,M}} \quad \text{(A17c)}$$

Authors' Note: Rebalancing Algorithm

The algorithm performing all calculations and simulations has been implemented in MATLAB© for this article.

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