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Reducing Climate Transition Risk in Central Banks' Asset Purchasing Programs

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Abstract In this paper we analyse whether and how a central bank can pursue the objective to lower its exposure to climate-related financial risks in its asset purchase programs while meeting the criteria that define the eligible universe of assets, including market neutrality. Despite focusing on the analysis of European Central Bank (ECB)'s asset purchase program and its exposure to climate transition risk, our approach and results can be applied to other central banks. We first prove analytically that under a strict market neutrality principle, the ECB's corporate bonds' portfolio is completely determined and climate transition risk cannot be reduced. We then show that under a weaker market neutrality principle, it is possible to construct a portfolio with lower exposure to climate transition risk than the current one. We provide a simple algorithm to produce examples of such portfolios. Our results contribute to support central banks in the assessment of their exposure to climate-related financial risks, and in the introduction of climate change considerations in their assets purchase programs.

1 Introduction

Climate change has been traditionally considered as an ethical issue for businesses and investors Scholtens [2006]; Kaesehage et al. [2019]. In this framing, the concern about economic activities that either negatively or positively im-

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pact on climate change is limited to those actors that are actively engaging with corporate social responsibility.

More recently, while the analysis of investors' exposure to climate-related financial risks has gained academics attention (Dietz et al. [2016]; Battiston et al. [2017]), climate change has been recognised by financial supervisors as a source of individual and systemic financial risk (NGFS [2019]; Bolton et al. [2020]). This latter framing makes the issue of engagement in climate change more general because an appropriate management of risk is of concern for all businesses and investors.

The assessment of climate-related financial risks poses several challenges. One the one hand, information on Greenhouse Gas (GHG) emissions has been shown to be relevant for banks' lending decisions Herbohn et al. [2019], as well as for investors' risk adjusted returns Liesen et al. [2017]. On the other hand, the sustainability performance of an investment is highly sensitive to the type of indicators utilised Scholtens [2010]. In this regard, the question of whether and how investors can reconcile the objective of lowering their own exposure to climate-related financial risks with other objectives (e.g. climate impacts, or financial performance) has remained open.

In this context, several central banks and international financial institutions have recognised the relevance of climate change for their financial stability mandate, including the European Central Bank[1]), and the International Monetary Fund [2]. Nevertheless, central banks have not been able yet to assess their portfolio's exposure to climate-related financial risks, in particular in the context of the asset purchasing programs, known as Quantitative Easing (QE) that they have been carrying out both in the aftermath of the 2008 financial crisis and in response to the 2020 COVID-19 pandemic. This is a main limitation because the QE programs have injected a massive amount of liquidity in the market. For instance, the ECB's Pandemic Emergency Purchase Programme (PEPP) has a 1,850 billion Euro envelop.[3]

Our analysis aims to assess this research gap that has important implications for business ethics. The main research question we address in this paper, is whether and how a central bank can pursue the objective to decrease its exposure to climate-related financial risks in its asset purchase while meeting the criteria that define the eligible universe of assets.

There is a debate on whether the ECB could go beyond the so-called principle of market neutrality (i.e. to follow an investment strategy that reflects the proportion of assets values in the market) in the context of climate change. The ECB itself has argued that "market neutrality might be problematic as a benchmark given that the markets have failed to produce climate-efficient

[1] See Lagarde's speech on Feb. 2020, https://www.ecb.europa.eu/press/key/date/2020/html/ecb.sp200227_1~5eac0ce39a.en.html

[2] See Managing Director Georgieva statement in 2019 https://www.bloomberg.com/news/articles/2019-10-16/imf-will-include-climate-in-country-analysis-georgieva-says

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

outcomes"[4]. Further, the ECB's President has stated that "The European Central Bank must question whether mirroring the composition of the bond market in its asset purchases is appropriate in light of climate risks" [5]).

Cojoianu et al. [2020] find that the likelihood of a an energy company bond to be part of the PEPP increases with the GHG intensity of the issuer. The policy brief by Dafermos et al. [2020] finds that there is a carbon skew in the Corporate Sector Purchase Programme (CSPP) portfolio, and suggest two strategies in which carbon-intensive bonds are replaced with more climate-friendly bonds.

Our paper complements these analyses that focus on GHG emissions, by bringing in the bond issuers' technological profile. Indeed, while it has been increasingly recognized that GHG accounting faces some limitations Busch et al. [2020]; Berg et al. [2019], granular information on the technological profile of the issuer is considered as fundamental to assess the climate transition risk exposure of the activity (see e.g. PACTA tool[6] and Battiston et al. [2020].

Moreover, there is lack of clarity on exactly how the market neutrality principle constraints the ability of ECB to integrate climate risk in its unconventional monetary policies. Most importantly, it is still unclear if and under which conditions the ECB could reconcile, in its asset purchase, climate risk considerations with the market neutrality principle.

We contribution to the research and policy debate as follows. We first define a strict principle of market neutrality, which requires to invest in corporate bonds proportionally to the amount outstanding security. This constraint adds up to the criteria that define the eligible bond universe (e.g. credit quality and residence of the issuer, maturity, etc.), and criteria regarding member states quotas. We demonstrate analytically that under a strict market neutrality principle, the ECB's PEPP portfolio is completely determined and there is no room for rebalancing the portfolio in order to lower exposure to climate risk. This means that, if markets do not price climate transition risk, then it is not possible to reconcile the market neutrality principle with climate change considerations.

Then, we define a weak market neutrality principle which requires to invest in corporate bonds proportionally to the amount outstanding by Climate Policy Relevant Sector (CPRS) Battiston et al. [2017]). This classification of economic activities overcomes some of the limitations of GHG accounting, it is fully compatible with the EU Taxonomy, it is immediately applicable by all investors because it is based on international standards and it covers both low carbon and high carbon activities Monasterolo [2020]. For its characteristics, it has been increasingly used by financial supervisors to assess investors' ex-

[4] Speech by Isabel Schnabel, Member of the Executive Board of the ECB, at the European Sustainable Finance Summit, Frankfurt am Main, 28 September 2020, https://www.ecb.europa.eu/press/key/date/2020/html/ecb.sp200928_1~268b0b672f.en.html

[5] Speech by C. Lagarde at United Nations Environment Programme Finance Initiative event on Oct. 13 2020 https://www.bloomberg.com/news/articles/2020-10-14/lagarde-says-ecb-needs-to-question-market-neutrality-on-climate

[6] https://2degrees-investing.org/resource/pacta/

posure to climate transition risk Battiston et al. [2020], EBA [2020], ESMA [2020].

We show analytically that under the weak neutrality principle, there is some room for rebalancing the ECB's PEPP portfolio in order to lower its exposure to climate risk, while respecting all other criteria. Further, we develop an algorithm to produce, under the weak market neutrality principle, examples of ECB's PEPP portfolios that are compliant with the eligibility criteria but, importantly, are less exposed to climate-related financial risk than the current one. In simple terms, the weak neutrality principle implies to invest proportionally 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 less carbon intensive activities. This means for instance within the fossil sector to increase exposure to firms with higher share of gas relatively to coal in their production. Similarly, in the utility electricity sector, this means to increase the exposure to firm with higher share of renewable sources. In our analysis, under the weak neutrality principle, we find alternative eligible portfolios with a rebalancing of about 6% of the total portfolio value.

While we focus our analysis on the ECB's CSPP and PEPP, the methodology that we develop and some of the results can be extended to other central banks worldwide. The structure of the paper is as follows. We first describe the criteria of asset purchase programmes (Section 2. We proceed by describing the notion of climate transition risk (Section 3. We then derive the main analytical results under the notions of strong and weak market neutrality. Further, we report the results on the construction of alternative portfolios with lower level of risk (Section 5). Finally we provide some concluding remarks (Section 6.

2 Asset purchase programme

As an answer to the financial crisis first, and to the Covid-19 pandemic subsequently, the ECB has implemented multiple unconventional monetary policy operations. In the broader context of the so-called Asset Purchase Programme (APP), two specific measures have been directed to corporate debt: the Corporate Sector Purchase Programme (CSPP, 2016 onward) and the Pandemic Emergency Purchase Programme (PEPP, 2020 onward). Both programmes target corporate securities and share the same eligibility criteria as listed in Table 1 below.[7]

[7] 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`.

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 shall 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 pre-defined benchmark, reflecting all eligible outstanding issues. The pre-defined benchmark is defined by "market capitalisation" as per criterium 7 above.
9	Limited purchases	The Eurosystem applies a maximum issue share limit of 70% per corporate bond on the basis of the outstanding amount.

Table 1 Eligibility criteria for the CSPP/PEPP programs.

3 Climate transition risk

Climate transition risk is understood here as the financial risk associated with the transition to a low-carbon economy Monasterolo and Battiston [2020]; Battiston et al. [2017]. In particular, central banks and financial supervisors are concerned by scenarios of disorderly low-carbon transition where climate policies are introduced late and investors cannot fully anticipate the policies' impact on their business NGFS [2019].

In this context, we classify economic activities of firms that issue corporate bonds in the Euro Area according to the Climate Policy Relevant Sectors (CPRS) classification developed in 2017 by Battiston et al. [2017] to classify individual economic activities according to their climate financial risk exposure. These are defined as economic activities, identified at the NACE 4 digit level, that could be affected positively or negatively (and potentially becoming "stranded assets") in a disorderly transition. Thus, they are relevant for assessing climate transition risk.

CPRS are provided at different level of granularity based on the energy technology used by the company's activity. CPRS1 is the most aggregate one, yielding 6 sectors - i.e. fossil fuel, utility, energy intensive, buildings, transportation, agriculture. The CPRS2 allow us to extend the original classification by increasing the granularity of breakdown by energy technology in the high/low-carbon sectors (e.g. primary energy/fossil/oil, secondary energy/utility/wind, etc), and to allow correspondence with the EU Taxonomy for eligible sustainable activities. By increasing the granularity of some sectors (e.g. fossil fuels/coal, fossil fuels/oil, fossil fuels/gas), we obtain about 20 subsectors related to the main types of different technologies that are relevant for the low-carbon energy transition. The economic activities belonging to CPRS are identified considering three main criteria:

- The direct and indirect contribution to GHG emissions;
- The relevance for climate policy implementation (i.e. their costs sensitivity to climate policy change, e.g. the EU carbon leakage directive 2003/87/EC)
- The activity's role in the energy value chain.

The CPRS allows to overcome the limits of pure classification of exposures based on GHG emissions and adds a climate risk connotation to the NACE 4-digit sector classification, which alone doesn't provide any proxy of climate risk, it does not carry any information on the energy technology mix, nor on the relevance for climate policy implementation. In the following, we use CPRS1 to define one of the constraints for the portfolio construction and CPRS2 as one of the criteria over which we can lower the level of transition risk.

4 Strong and weak market neutrality

Under the criteria defined in Table 1, which we will call *strong market neutrality* as in Definition 1, it is possible to show that the ECB's portfolio is completely determined, i.e. the ECB has only one possible portfolio that respects all criteria. Hence, the ECB has no leeway to reduce its exposure to climate transition risk. The results are formalised in proposition 1. There was already an intuition for this result, but to our knowledge, it has not been formalised yet. By clarifying this issue, we help the research and policy debate to move forward.

More in detail, the intuition of this result is as follows. We assume that bond issuers can be classified in terms of certain sectors of economic activities, indexed as S belonging to macro-sectors, indexed as MS. We further assume that it is possible to attribute to each issuer a level of climate transition risk, denoted as Q_s. Later we will use CPRS1 and CPRS2 as a specific classification. However the result holds more in general. Based on the two above assumptions, we can then establish a partial order within the macro sector, i.e. it is possible to find sectors less exposed to climate transition risk than the others in the same macro sector. We define the risk for a portfolio P 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 sectorial composition, it is possible to test which one has a lower exposure to climate transition risk, i.e. if $Q_{P_1} < Q_{P_2}$. As it turns out, strong market neutrality implies that given the current ECB portfolio, there is no other feasible portfolio with lower transition risk.

Definition 1 (Strong market neutrality) We speak of strong market neutrality if criteria 1-9 as defined above 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 1, her portfolio is completely determined.*

Note that the proposition does not imply that all weights are fully determined, i.e. the ECB can still decide how much to invest in a specific issue, in the limits of criteria 7 to 8. Hence, discrepancies between the universe of eligible bonds and the actual ECB portfolio may exist, i.e. there could be bonds in principle eligible 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 or rating considerations. Also, the classification of issuers as public undertakings could imply limited deviations.

Since the uniqueness result of Proposition 1 is determined by the definition of strong market neutrality, we introduce a weaker definition of market neutrality, as described in definition 2. The latter is based on the amount outstanding at the level of sectors as opposed to the the level securities as in Definition 1.

For the purpose of this paper, we define sectors following the CPRS classification Battiston et al. [2017], as discussed in Section 3. More precisely, we will impose that the amount outstanding in each given CPRS1 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 1-9 and, at the same time, reach a lower level of climate transition risk for its portfolio.

Definition 2 (Weak market neutrality) We speak of weak market neutrality if criteria 1-7 and 9 as defined above simultaneously hold, while criterium 8 is substituted as follows: purchase must be proportional to the amount outstanding in each given macro-sector (CPRS1).

Under this weaker definition of market neutrality, we can demonstrate that the climate transition risk of the portfolio can be reduced as formalised in Proposition 2 below.

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

5 Alternative portfolios

In this section, we show how the current ECB portfolio can be rebalanced to achieve a lower level of climate transition risk, under the weak market neutrality constraint defined in 2.

5.1 Data

For the purposes of this study, we assume that the ECB portfolio respects the constraints as defined in 1, and hence it corresponds to the eligible universe of securities. We gather the bond portfolio as published from the ECB, consisting of 1'588 bonds, issued by 332 unique issuers, as of November 6^{th}. 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 Thomson Reuters Eikon: country of domicile, organization parent, NACE classification 4 digits, best-of issuer or issue rating, amount outstanding, green bond flag. Issuers are consolidated to the immediate parent where applicable, for example in the case of financial vehicles, in order to correctly assign the NACE sector and hence CPRS1 and CPRS2, following Table 2 above, to the bond. Weights in the ECB portfolio are assigned consistently with the amount outstanding. As additional measures of greenness, we use the variable "Exposure to New Energy" retrieved from Bloomberg New Energy Finance (BNEF), which we take as proxy of the share of revenue of the firm from low-carbon technology.

We also retrieve from BNEF the the list of green energy projects in Europe and we derive a measure of greenness, with the following procedure:

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-decomissioned and non-abandoned projects from 2014 onward
2. Owners are consolidated to the first listed entity where available, or to the first non-government parent when unlisted
3. As some projects miss the value, cost curves are estimated at 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 Thomson Reuters Eikon
6. The greenness indicator is computed over 3-years rolling window from 2016 to 2019 as $GI_y = \frac{\sum_{y-2,y-1,y} CAPEX_{Green}}{\sum_{y-2,y-1,y} CAPEX_{All}}$

The current composition of the ECB portfolio is described in Figure 1 below by CRPS1 and country of domicile.

Figure 1 already shows some challenges for portfolio rebalancing. Indeed, the ECB cannot alter the country composition and must, under the weak market neutrality assumption, maintain the CPRS1 proportion constant. This implies that rebalancing will be possible for some countries, for a limited share of the portfolio weight. Despite this, we show that it is possible to still do a rebalance toward companies less exposed to climate transition risk as long as adequate measures of grenness are defined. In the context of this paper, we use three measures, depending on the CPRS considered:

– CPRS2, where it is possible to determine a granualr energy technology profile and thus a ranking of exposure climate transition risk;

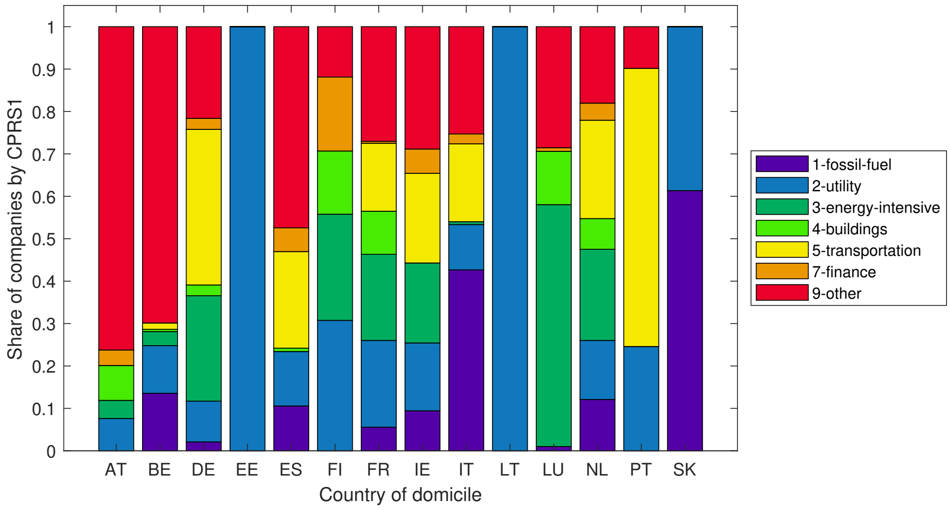

Fig. 1 Exposure of the ECB portfolio by country of domicile and CPRS2, after reclassification, as of November 6^{th}

- The computed capex greenness indicator for utilities;
- BNEF's "Exposure to new energy: when it's not possible to use either approach.

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5.2 Portfolio climate transition risk

As defined in Section 2, climate transition risk is defined as Q_s and depends on the sector S in analysis. Since it is possible to establish, within a certain macro sector MS an order of climate transition risk such that $Q_{S_1} < ... < Q_{S_n}$, it is hence possible to achieve a situation where, for two portfolios P_1 and P_2, it holds that $Q_{P_1} < Q_{P_2}$. As mentioned in Definition 2, we define sectors and macro sectors according to CPRS1 and CPRS2 as in Battiston et al. [2017] and Battiston et al. [2020]. Where this is not possible, we apply further greenness variables to define a relative order of exposure to climate transition risk.

The summary of ranking criteria is provided in Table 2 below for each CPRS1:

Hence, following the approach in Table 2, we assume that a portfolio more skewed toward gas, rather than oil, is less exposed to climate transition risk. Hence, an investor willing to reduce her climate transition risk, still maintaining a constant exposure at the CPRS1 level, can move weight from oil to gas in order to reduce it.

<table>
<tr><th>CPRS1</th><th>Ordering rule</th></tr>
<tr><td>1-fossil-fuel</td><td>1-fossil|gas < 1-fossil-fuel* < 1-fossil|oil < 1-fossil|coal</td></tr>
<tr><td>2-utilities</td><td>utilities are classified according to their share of green capex as computed above. Utilities with a share larger than the median are considered to be less exposed. The order is applied to companies in the CPRS 2 ”2-utility-generation” only</td></tr>
<tr><td>3-energy-intensive</td><td>energy intensive companies are classified according to the greenness BNEF variables, where values are moved from companies with the maximum browness to the ones with lower browness</td></tr>
<tr><td>5-transportation</td><td>5-transportation|railways < 5-transportation** < 5-transportation|roads < 5-transportation|air</td></tr>
<tr><td>All others</td><td>No order is possible at the current stage</td></tr>
</table>

Table 2 Climate transition risk: order applied within CPRS1. (*): the CPRS 1-fossil-fuel refers to support or mixed activities that is not clearly possible to map to only one technology. (**) the CPRS 5-transportation refers to support and infrastructural activities which is not clearly possible to map to only one mean of transport.

For the purposes in the paper, we define a company as being *less exposed* to climate transition than another if its CPRS2 or defined greenness is lower than the one of the second company. In the same way, we define a company to be *more exposed* if the opposite is true.

It is clear that the procedure for the portfolio rebalancing is strictly dependent on two factors: 1) the chosen measure of exposure to transition risk; and 2) the definition of a company's business activity. In the context of the current paper, (1) is addressed as defined in Table 2 above, while for the purpose of (2) only the main NACE 4 digits activity is considered. While there are clear limitations behind this approach, i.e. that many companies have side activities whose impact gets to be 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 greenness based on the portfolio of activity of a certain company shall be object of further research. This may, for example, imply looking at the exact revenue shares of oil and gas integrated companies within 1-fossil-fuel, or at the share of manufactured electric vehicles within 5-transportation.

5.3 Portfolio rebalancing

The algorithm to rebalance the portfolio in order to reduce its exposure to climate transition risk proceeds iteratively. At each iteration, it increases the share of weight reallocated from bonds more exposed to climate risk bonds that are less exposed, while keeping constant the total exposure of the portfolio to each CPRS1 sector, the financial rating and maturity profile of the portfolio, as consistent with definition 2. Each bond is used only once, i.e. its weight can be modified (increased or diminished) only once in the iteration; this corresponds to saying that bonds are paired for the purpose of the recalibration. The procedure is illustrated as follows:

Algorithm 1: Portfolio reallocation algorithm, following the rules defined in Table 2. The algorithm exits when one of the following occurs: (i) the rating profile worsen; (ii) the maturity profile differs significantly from the original; (iii) 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 CPRS1 in CPRS1 list do
            Select all bonds in CPRS1
            if CPRS1 == "1-fossil-fuel" or CPRS1 == "5-transport" then
                Select all more exposed bonds in the given CPRS1, according to
                  the CPRS2 exposure;
                Pair each more exposed bond to a less exposed one in the same
                  CPRS1;
                Move weight constant 1/ω from more exposed to less exposed bond;
            else if CPRS1 == "2-utilities" then
                Select all more exposed bonds in the given CPRS1, according to
                  the CAPEX greenness indicator;
                Pair each more exposed bond to a less exposed one in the same
                  CPRS1;
                Move weight constant 1/ω from more exposed to less exposed bond;
            else if CPRS1 == "3-energy-intensive" then
                Select all more exposed bonds in the given CPRS1, according to
                  the BNEF greenness indicator;
                Pair each more exposed bond to a less exposed one in the same
                  CPRS1;
                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
        Increase ω and repeat
    else
        Keep last rebalanced weights set;
    end
end
```

The portfolio reallocation algorithm works on CPRS 1, 2, 3, 5; leaving out the remaining CRPS sectors. This is due to the lack of a consistent way to clearly classify business activities in terms of their exposure to climate transition risk because of (1) lack of granularity in CPRS2 or (2) lack of data for exposure to new energy or green capex. It is also important to consider that the ECB portfolio must keep the exposure constant not only by sector, but also by country; this clearly imposes limitations as some countries do not have eligible, less exposed to transition risk, bonds and hence weights for those countries cannot be recalibrated. As a general rule, a rebalance is possible only with respect to those large countries with a diversified bond universe.

It is also important to keep in mind that this exercise has been performed as in a situation of initial allocation, i.e. the alternative portfolio represents a possible different allocation at November 6th 2020. Hence, this paper does not account explicitly for the considerations, in terms of liquidity and prices, that the shift from a portfolio to the other would cause.

5.4 Results

The algorithm is run until the maximum weight (half of original in the current 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 an either positive or negative weight change. Given that bond weights can be adjusted only once (i.e. one addition or one reduction of weight), 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 impacts is on 98 unique issuers, out of 332 in the portfolio.

The results of the rebalance are shown in Figures 2 and 3 below, respectively for CPRS 1 and 5, and 2 and 3. The first part of the rebalance is run using the CPRS2 classification as a metric of exposure to climate transition risk, while the second part is run using the BNEF exposure to new energy for Energy intensive, and the CAPEX greenness for Utilities.

It emerges from the charts that, being still under a market neutrality approach, there is limited potential for portfolio rebalance, mainly as a consequence of the existing market structure. Despite this effect, it is still possible to move substantial weights away from highly exposed transportation vectors (air and roads) toward railways and supportive transportation activities; at the same time, for fossil fuels, weight is moved away from coal and oil to less polluting generations such as gas. A similar discussion applies to utilities and energy intensive sectors - i.e. two key sectors for the low-carbon transition - although here the limitations are even more significant. We noticed in fact that the energy intensive sector is strongly skewed toward more brown firms (having a BNEF exposure of 4), while very limited weight is associated with greener firms. Hence, rebalancing has limited reach, at least under our conservative scenario of weights movement. While there is more leeway for utilities, limits on both information and number of less exposed firms bite. It is important to note that, as run, the exercise is acting in a rather conservative way, moving weight from/to bonds only once, and never going beyond half of the original weight. More aggressive versions can be run, leading to a higher weight shift. For example, for a weight movement of 75% from more to less exposed bond, a total of 10% of the portfolio weight is moved from more exposed bonds to less exposed bonds - while it was approximately 6% in the base case.

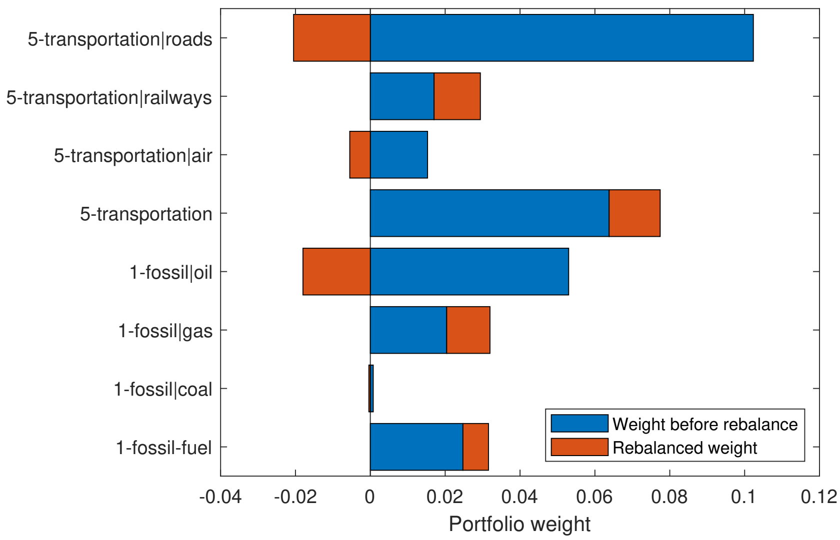

Fig. 2 Portfolio weights rebalance, CPRS 1 and 5. Blue bars represent total weight for a given CPRS2 before the portfolio rebalance, while red bars represent the portfolio weight moved away, or toward, a given CPRS2.

While the exercise can be replicated in different ways, it clearly shows that it is possible to rebalance the ECB portfolio toward a lower carbon risk respecting market neutrality. The exact how depends ultimately on the measure of climate transition risk chosen, which can leverage CPRS2 classification directly in some cases or comparable measures when this is not available.

6 Discussion and conclusion

In this paper, we show that a strict market neutrality principle determines completely the PEPP portfolio, leading to the following possible contradiction. If markets do not price climate transition risk, then the market neutrality principle prevents any action to lower the climate transition risk of the ECB's PEPP portfolio. In contrast, under a weak market neutrality principle, there is some room for rebalancing the ECB's PEPP portfolio and lowering its exposure to climate transition risk, while respecting all other criteria. We develop an algorithm to construct examples of alternative ECB's PEPP portfolios that are compliant with the eligibility criteria but less exposed to climate transition risk than the current one. The alternatives portfolios are characterizing by a rebalancing of about 6% of the total portfolio value. They are obtained by increasing the amounts invested in companies that are involved with less carbon intensive activities.

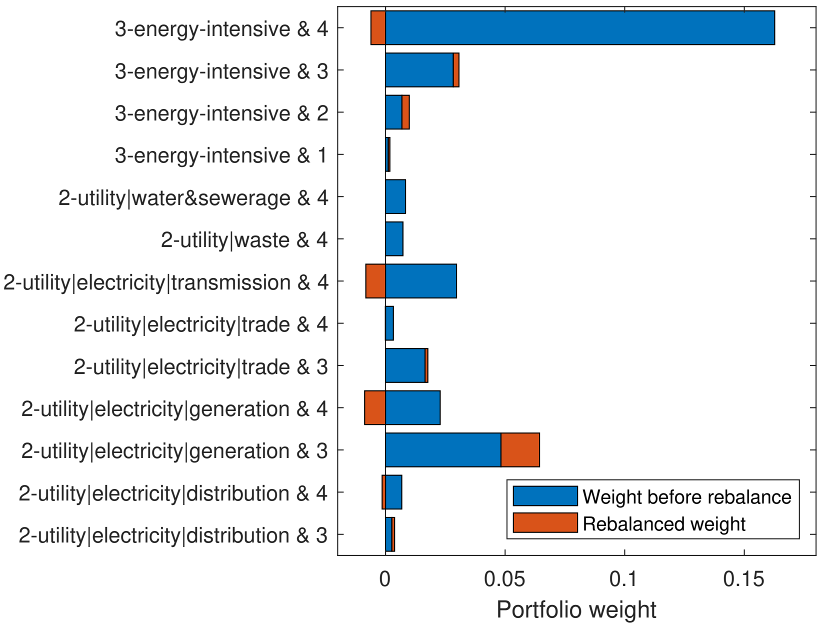

Fig. 3 Portfolio weights rebalance, CPRS 2 and 3. Blue bars represent total weight for a given CPRS2 before the portfolio rebalance, while red bars represent the portfolio weight moved away, or toward, a given CPRS2. After each CPRS2, a value from 1 to 4 is reported indicating the original BNEF greenness or the converted capex indicators. Lower numbers represent greener companies.

An important remark is that the rebalancing we obtain in our analysis satisfies the constrain that the investment is proportional to the total amount outstanding issued by issuers in each Eurozone member state. This constraint greatly reduces the possibility to rebalance investments from higher transition risk to lower transition risk bonds. More in general, the bond market may not offer, in specific countries or sectors, enough potential candidates for rebalancing. Further, there are more high than low transition risk bonds, implying that there is a limited number of "destination" bonds for the rebalancing algorithm.

The following limitations should be considered when interpreting our results.

A first limitation pertains the variables we use to capture the levels of exposure to transition risk. The variable Exposure to New Energy is taken as given from BNEF and we have not carried out a firm by firm validation. Further, we classified issuers based on the core NACE 4 digit code. When firms operate in multiple sectors one should take into account the corresponding shares of revenues. This requires substantial manual validation which will be done in future work.

A second limitation pertains the greenness measures. While they are comparable within the same CPRS1, they are not necessarily comparable across different CPRS1. This does not affect our current results which is based on partial order, but could be an issue for metrics that require a global order. Also, the granularity of the date varies across CPRS2 sectors. In general, all considerations shall be done at the level of firms' revenues shares in each CPRS2, but this is not possible at the current stage and should be object of further research

A third limitation is about liquidity and price impact considerations (which are not considered in our current implementation). Implementing purchases and sales of bonds has clear impacts on the market given the size of the ECB purchases, especially on smaller or less liquid issues. Hence, implementation aspects should be considered as well.

A 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.

As above, 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, i.e. it is possible to write:

$$For S_1, ..., S_{k_1} \in MS_1 : Q_{S_1} < Q_{S_2} < ... < Q_{S_{k_1}}, \tag{1a}$$

$$For S_{k_1+1}, ..., S_{k_2} \in MS_2 : Q_{S_{k_1+1}} < ... < Q_{S_{k_2}}, \tag{1b}$$

$$..., \tag{1c}$$

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

For the bond markets, it holds:

$$S_{U_s} = \sum_{i \in \mathbb{1}_{\{b_i \in S\}}} b_i \tag{2}$$

and

$$S_{s,count} = \sum \mathbb{1}_{\{n_j \in S_s\}} \tag{3}$$

where S_s represents the total amount outstanding for sector s, and $S_{s,count}$ represents the number of issuers for sector s. We can define the sectorial structure of the portfolio as:

$$S_U = [S_{U_1}; S_{U_2}; ...; S_{U_S}]. \tag{4}$$

Clearly, the market portfolio will be characterised by a certain climate transition risk Q_U defined as:

$$Q_U = \sum_{s \in S} \frac{S_{U_s}}{\sum_s S_{U_s}} Q_{S_s}. \tag{5}$$

The investor's portfolio has a total known amount D to be invested in the market according to criteria 1-9 above. 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:

$$w_i = \frac{x_i}{D} \tag{6}$$

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 above. 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

$$S_{D_s} = \sum_{j \in 1_{\{n_j \in S\}}} w_j D, \tag{7}$$

leading to the following vector of sector level exposures:

$$S_D = [S_{D_1}; S_{D_2}; ...; S_{D_S}]. \tag{8}$$

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

$$w_j = \frac{b_j}{\sum_j b_j} \tag{9}$$

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 relation between S_D and S_U is implied, hence proving the Proposition.

First, we substitute w_j in Equation 7 following the proportionality as in Equation 9 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:

$$S_{D_s} = \frac{D}{B} \sum_{\{j \in s\}} b_j \tag{10}$$

Where the last term in the equation is exactly S_{U_s}, implying a proportional relation which cannot be avoided as long as Equation 9 holds.

Moreover, from the above it follows also from the definition in Equation 5 that $Q_D = Q_U$, i.e. the investor cannot influence its climate transition risk profile.

Proof of Proposition 2

We move in the same economy and bond market described in the proof of Proposition 1 above, i.e. we suppose equations 1 to 8 still holds. For the definition of weak market neutrality, Equation 9 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:

$$MS_{D_m} = \sum_{s \in m} S_{D_s}, \tag{11a}$$

$$MS_{U_m} = \sum_{s \in m} S_{U_s}. \tag{11b}$$

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

$$MS_D = [MS_{D_1}; MS_{D_2}; ...; MS_{D_M}], \tag{12a}$$
$$MS_U = [MS_{U_1}; MS_{U_2}; ...; MS_{U_M}]. \tag{12b}$$

Following the definition of weak market neutrality, we know the following equation holds for the macro-sector level, replacing Equation 8:

$$MS_{D_m} = \frac{D}{B} MS_{U_m}, \tag{13}$$

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

$$MS_{D_m} = \sum_{j \in m} w_j D, \tag{14}$$

$$MS_{U_m} = \sum_{j \in m} b_j \tag{15}$$

by substituting we obtain:

$$\sum_{j \in m} w_j D = \frac{D}{B} \sum_{j \in m} b_j. \tag{16}$$

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 necessary mimicking the exact structure of the market benchmark but just its macro-sectorial composition - hence, yielding the proof.

Moreover, it is possible to find a portfolio that has less climate transition risk, i.e. for which it holds $Q_D < Q_M$. Indeed, given equations (1a)-(1d), it is possible to achieve a weight combination under which it simultaneously hold:

$$Q_{MS_{1,D}} < Q_{MS_{1,M}} \tag{17a}$$
$$... \tag{17b}$$
$$Q_{MS_{N,D}} < Q_{MS_{N,M}} \tag{17c}$$

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