A carbon risk assessment of central banks' portfolios under 2°C aligned climate scenarios

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Abstract
A 2°C aligned transition could generate opportunities for sustainable growth, competitiveness and financial stability. Nevertheless, policy uncertainty creates new sources of risks. Traditional financial and climate economics models are not able to price countries’ (mis)alignment with the 2°C target. We develop a novel climate stress-test methodology to price climate transition risks and opportunities in individual financial contracts and we apply it to the Austrian National Bank’s portfolio. First, we develop asset-specific models to price in climate transition risk in today’s value of equity, loans, corporate, sovereign bonds under feasible climate policy scenarios by 2030. Then, we introduce the climate spread metric and we estimate the changes in sovereign bonds’ value by 2030, considering country-specific fiscal and debt conditions, and the carbon-intensity of their GDP and revenues. We focus on sovereign bonds because they represent the largest share of central banks’ portfolios and provide a proxy of countries’ competitiveness and financial stability. Finally, we identify the largest gains and losses for investors that could have systemic effects. The alignment to a credible 2°C trajectory can strengthen the country’s fiscal and financial position, while a misalignment to 2°C trajectory can increase sovereign bonds’ yield (climate spread). Negative shocks are induced by the inability of policy makers to timely introduce effective policies, and of investors to timely adapt their business. Largest negative shocks (losses) are associated to carbon-intensive activities, while positive shocks (gains) are associated to low-carbon ones.

Keywords: climate stress-test, climate transition risk, 2°C opportunities, central bank’s portfolio, climate spread, sovereign bonds’ evaluation.

JEL: D85, D86, E58, G01, Q54

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1. Introduction
Achieving the goal to limit global temperature increase below 2°C by 2100 requires an urgent scaling-up of investments in the low-carbon energy transition. In the European Union (EU), investments needed in renewable energy are estimated in about € 180 billion (bn) per year by 2050 (HLEG 2017). Recently, the crucial role of finance in this process was acknowledged (Zadek and Kharas 2018, HLEG 2018, UNFCCC, 2016) but investments in low-carbon energy sectors are far from what required to fill in the green investment gap (IRENA CPI, 2018). In particular, the financial sector is not internalizing yet climate risks in their portfolio management strategies (de Greiff ea. 2018). This means that the risk associated to holding assets that could lose much of their value as a consequence of climate risks (i.e. the so-called carbon stranded assets) is not yet priced in assets evaluation. Indeed, limiting global temperature increase below 2°C will require a large amount of fossil fuels to remain in the ground, becoming unburnable (Leaton 2012) and negatively affecting revenues of companies whose business is linked to fossil fuels, and of investors exposed to such companies. Mispricing of potential stranded assets, in turn, could lead investors to accumulate undesired exposures to climate risks through their portfolio’s management strategies. If large asset classes are interested, implications for price volatility and financial stability could emerge. Indeed, the high interconnectedness of the financial system and the financialization of the real economy could induce large prices volatility when investors are not able to anticipate (and thus to price in) technological and policy shocks associated to the low-carbon transition (Monasterolo ea. 2017). Nevertheless, preserving prices and financial stability is traditionally at the core of central banks’ mandates (e.g. the European Central Bank, ECB). Thus, sources of financial risk stemming from climate change, and in particular to a mismanaged transition to a low-carbon economy, should be of interest for central banks. Central bankers and financial regulators’ awareness of the new risks imposed by climate change on the stability of individual financial institutions and the financial system increased. In his famous speech at Lloyd’s, the Governor of the Bank of England Mark Carney pointed out the financial system is exposed to climate physical risks and climate transition risks, which could lead to major losses for the economy, finance and insurance industry (Carney 2015, Batten ea. 2016). Dietz ea. (2016) found that the climate Value at Risk of the financial system due to climate physical risk ranges between $2.5 and $24.2 trillion (tn) by 2100. The first climate stress-test of the financial system by Battiston ea. (2017) shows that the exposure of individual financial actors’ equity portfolios to climate-policy-relevant sectors (i.e. sectors that are directly or indirectly responsible for greenhouse gases (GHG) emissions and thus more vulnerable to climate policies) is considerable, reaching 45% of the equity portfolio of pension funds and investment funds. In addition, potential amplifications of losses due to financial interconnectedness could occur. Finally, refining the climate stress-test methodology for pricing climate risks into development banks’ loans, Monasterolo ea. (2018) find that even limited climate policy shock would lead Chinese development banks to financial distress given their current leverage, with systemic implications. Thus, the introduction of too-late and badly designed climate policies could come with a significant
risk for those investors who are locked-in into high-carbon investments (the so-called climate transition risk, Batten et al. 2016, Dunz et al. 2018).

The potential realization of climate-related systemic risks to the financial system calls for the attention of central banks and financial regulators. Recently, the discussion on what role central banks could play to align finance to sustainability, also through green monetary policies aimed to signal the market, has emerged (Monasterolo and Raberto 2018, Dafermos et al. 2018). In 2015, the governor of the Bank of England (BoE) Mark Carney talked about a “tragedy of the horizon” arising from the misalignment between climate long-term perspective and the shorter-term view of monetary policy and financial regulation (Carney 2015). Several central bankers followed (Schotten et al. 2016, Signorini 2017; Nowotny 2018; Villeroy de Galhau 2018). The head of the European Central Bank (ECB) Mario Draghi, who stated the need to introduce climate factors into financial risk assessment (Draghi 2017), and the need for the ECB to assess its exposure to climate risks. As highlighted by Dombret (2017), “we may have identified the risks, but we don't know how material they are”. At this regard, standardized metrics and methods (e.g. climate stress-test) for investors' climate-related financial disclosure was advocated by the Financial Stability Board (FSB)'s Task Force for Climate-related Financial Disclosures (TCFD) in its final recommendations (TCFD 2017), by the European Commission (EC)'s High-Level Experts Group on Sustainable Finance (HLEG), and recently by central bankers belonging to the "Network for Greening the Financial System” (Banque du France 2017). In the first 2018 meeting of the network, the head of the French Central Bank Mr. Villeroy de Galhau, declared that central banks need “forward-looking stress test assessing the comprehensive interaction between climate change and assets and liabilities” (Villeroy de Galhau 2018). Some central banks have also started developing research aimed at identifying and quantifying the relevance of climate-related financial risks (Regelink et al. 2017).

However, central banks don't yet dispose of in-house, tailored tools to assess their and investors’ portfolios exposure to such risks, as well as their impact on climate action via market signaling through their conventional and unconventional monetary policies.

With the aim to fill in this gap, we further extent the climate stress-test framework based on Battiston et al. (2017) and Monasterolo et al. (2018) to provide the first carbon risk assessment of central banks’ portfolios, and we apply it to the non-monetary policy portfolio of the Oesterreichische Nationalbank (OeNB; Central Bank of Austria). The carbon risk assessment consists of a novel methodology that allows to factor climate transition risk into financial assets’ (corporate bonds, equity holdings and sovereign bonds) value, under milder or tighter climate policy scenarios by 2030. With the carbon risk assessment, we can evaluate the change in the actual value of corporate bonds, equity and sovereign bonds as a consequence of unanticipated climate policies in the mid-term (i.e. by 2030), based on the change in sectors’ market share. Positive or negative shocks on sectors’ market shares

2 Behind the curve? The role of climate risks in banks’ risk management. Remarks at the National University of Singapore. 02.10.2017. Available at: https://bit.ly/2x7kEWv
depend from the inability of governments to timely implement climate policies, and of investors to anticipate them in their portfolio management strategies. We consider climate policy shocks are associated to the introduction of mild or tight climate policies i.e. a carbon tax aimed to keep global CO2 emissions concentration respectively to 500 parts per million (ppm) or 450 ppm.

Our approach is modular. First, we estimate the effect of climate policy shocks affecting the change in market shares of energy and electricity sectors (i.e. fossil fuel and renewable energy-based) of economic activity in specific countries and regions by 2030, using the LIMITS Integrated Assessment Models (IAMs). Then, we model the transmission of the shocks in market shares on changes in sectors’ Gross Value Added (GVA), and in equity and bonds’ value and yields by country. In the case of sovereign bonds, we introduce the notion of “climate spread” and we compute it as the change in 10-years bond’s yield across the climate policy scenarios by 2030, per country of issuance. Finally, we identify the exposures to specific assets leading to the largest gains and losses for the central bank’s portfolio. The shocks should be interpreted as potential gains and losses on individual contracts associated to a late and disordered transition to tight climate policy scenarios by 2030, aimed to bring the economy on a low-carbon path.

Our methodology is transparent and thus replicable and customizable, and able to capture the multiple relevant dimensions for central banks’ climate-finance decision-making. This is the first time that a carbon risk assessment methodology for central banks’ portfolios is proposed and applied through a joint collaboration between research and central banks.

The paper is organized as follows. Section 2 describes the data and database used. Section 3 describes the carbon risk assessment methodology for corporate bonds, equity, and sovereign bonds, for which we introduce the notion of climate spread. Section 4 presents the results of the climate policy shocks to OeNB’s portfolio of sovereign bonds and the estimates of the climate spread under milder and tighter climate policy scenarios by 2030. Section 5 concludes with a discussion of the policy relevance of our results for central banks’ monetary and macroprudential measures.

2 Data

In this section, we present the data and databases used for the analysis that include OeNB’s portfolio data; the NACE Rev2 (Nomenclature statistique des activités économiques dans la Communauté européenne) classification of sectors of economic activity adopted by Eurostat; the NAICS 2017 (North American Industry Classification System) classification of sectors of economy activity that is mostly used in the US; the British Petroleum (BP)’s Statistical Review of World Energy 2018 for energy data.

2.1 OeNB’s portfolio data

OeNB’s portfolio contains 1386 entries as June 2018. Exposures to sovereign bonds represents its majority, followed by corporate bonds and equity holdings, completed by a small share of other financial products.
Each issuer is associated to a country code and a financial instrument (MiFID asset class), which is in turn associated to a NACE Rev2 4-digit code and to a weight on the overall OeNB’s portfolio. For less than 3% of the portfolio it was not possible to assign a NACE 4-digit code. Therefore, we decided to exclude the contracts with missing code from the analysis.

2.2 Classification of sectors of economic activity
We follow two classifications of economic sectors, i.e. the NACE Rev2 (Nomenclature statistique des activités économiques dans la Communauté européenne), which is adopted by Eurostat to classify the economic activities at a 4-digit level, and the NAICS 2017 classification\(^3\), mostly used in the US. Indeed, by mapping NACE 4-digit sectors into NAICS (North American Industry Classification System) sectors we obtain a more precise description of sectors’ technology, in particular for energy and electricity-related investment. NACE sectors are listed from A—Agriculture, forestry, and fishing to U—Activities of extraterritorial organizations and bodies. Thus, in principle, it would be possible to associate the exposure of a specific financial instrument to a specific sector of economic activity with a level of detail that would allow us to distinguish between carbon-intensive (and thus highly exposed to climate policies) and low-carbon sectors. Nevertheless, this classification is subject to some limitations, in particular as regards the classification of activities within a relevant sector for our analysis, i.e. sector B – mining and quarrying, and sector D – Electricity, gas, steam, and air conditioning supply, and their contribution to Greenhouse gases (GHG) emissions. Indeed, the level of aggregation of the NACE Rev2 classification of economic activities for which GHG emissions are available hides the heterogeneity of the contribution of different activities classified within the same sector to GHG emissions. GHG emissions for activity at the NACE 4-digit level are not available, thus preventing us from the tempting option of classifying sectors by their emissions’ intensity. For instance, sector C-Manufacturing, which contributes to 26% circa of cumulative CO2 emissions, includes a broad range of activities such as Manufacture of food products, beverages, and tobacco products (CA), Manufacture of coke and refined petroleum products (CD), and Manufacture of computer, electronic, and optical products (CI), which currently cannot be disentangled (Monasterolo ea. 2017).

2.3 Energy data
Data on energy and electricity production and prices by fossil fuel (natural gas, oil, coal), nuclear and renewable energy technology (hydropower, solar, wind, biomass), country and year are provided by the British Petroleum (BP)’s Statistical Review of World Energy 2018. We use data on energy and electricity production by source and country to compute the value added of each technology and its share on total electricity production by country.\(^4\) This information

\(^3\) https://www.census.gov/eos/www/naics/
\(^4\) In this version of the paper, we don’t consider differences in electricity prices by sources.
is then used to compute the impact of climate policy shock on the climate spread and on the sovereign bonds’ value (see methodology, section 3.3).

3 Methodology
In this section, we present a novel analytical framework for the carbon risk assessment of central banks’ portfolios. It builds on the climate stress-test methodology by Battiston ea. (2017) and Monasterolo ea. (2018) but introduces key novelties, such as the notion of climate spread. We apply our methodology to three types of assets included in OeNB’s portfolio, i.e. corporate bonds, equity holdings and sovereign bonds. The asset pricing evaluation models apply to specific asset types considered, and thus could be applied not only to the central banks’ portfolios. First, we model the impact of mild or tight shocks led by the unanticipated introduction of mild or tight climate policies by 2030 on the change in market share of energy and electricity sectors and technology (i.e. fossil fuel or renewable-energy based). Then, we formalize the shock’s transmission from the sectors’ market share to their Gross Value Added (GVA) by country, region and asset type. Third, we estimate the change in asset value due to climate risk, identifying largest gains and losses in the case of sovereign bonds by country, deriving the magnitude and sign of the shock on central bank’s portfolio’s value. To our knowledge, this is the first time that a carbon risk assessment methodology is developed for, and applied to, a central bank’s portfolio. The development of an evaluation methodology able to introduce climate considerations into the financial evaluation of specific assets under different yet feasible climate policy scenarios, is fundamental to provide a transparent carbon risk assessment of central banks’ portfolios. This is particularly relevant in the case of sovereign bonds, which represent the majority of central banks’ portfolios exposures, and were a main target of the expansionary unconventional monetary policies introduced in the US first and then in the euro area by the ECB (Eurosystem) in the aftermath of the 2008 financial crisis. Unlike traditional investors, central banks’ goal is not portfolio’s maximization but for most central banks, their mandate includes price and financial stability.

3.1 Valuation framework for corporate bonds contracts subject to climate policy shocks
We first consider the financial actor i (i.e. the central bank)’s investments in corporate bonds. For the point of view of investment risk, each corporate bond contract is represented here as a distinct issuer j. We want to develop a valuation framework for corporate bonds’ portfolio that accounts for climate risk. In particular, we focus on a specific type of transition risk, i.e. climate policy shocks, consisting in the late and uncoordinated introduction by the governments of a mild or a tight carbon tax aimed to align the economy to a 2°C path.

5 This article is meant to be a methodological contribution. Thus, we show here the empirical application for the sole sovereign bonds, which represent the largest share of central banks’ portfolios. However, empirical analyses have been carried out also in the case of corporate bonds and equity and are available upon request.
The valuation model includes three time-steps: $t_0, t^*, T_j$, with $t_0 < t^* < T_j$, where $t_0$ denotes the time at which the valuation is carried out, $t^*$ denotes the time at which a climate policy shock (considered as the introduction of a climate policy in comparison to a baseline of no climate policy) potentially occurs, and $T_j$ denotes the time when investor $i$ receives the bond’s coupon from the issuer $j$. For the sake of simplicity, we consider an annual payment of bonds’ coupons, associated to a specific default probability of the issuer, and assume that all contracts have the same maturity. The investor $i$ receives the coupon value at the maturity $T_j$ from the bond issuer $j$. We then denote by $A_{i,j}(t_0, T_j)$ the financial valuation at time $t_0$ of the investment of $i$ in $j$. Accordingly, the valuation of $i$’s corporate bonds’ portfolio can be written as follows:

$$A_i(t_0) = \sum_j A_{i,j}(t_0, T_j).$$

(1)

3.1.1 Corporate bonds’ evaluation

The value of the corporate bond contracts is computed as the expected value of the bond, discounted at an interest rate that accounts for the risk associated to the bond. We consider the simpler case of the value of a ‘straight bond’ with fixed coupons, whose maturity is determined by changes in the discount rate, which incorporates both the general level of interest rates and the specific default risk of the bond being valued. In our case, this is linked to the operative performance of the issuer and its carbon-intensity (and thus the exposure to climate policy risk), and the climate policy introduced. We consider default premia that could vary across time, depending on the carbon-intensity of the sector of economic activity of the issuer (i.e. its NACE 4-digit and LIMITS sector), and the introduction of scenarios characterized by mild or tight climate policies. The value of the default premium is dependent on the profitability of the sector of economic activity hit by climate policy shock, based on the forecasts of the change in market-share computed by four Integrated Assessment Models (IAM) belonging to the LIMITS project whose results are accessible in an online database. The expected value of a corporate bond, expected to mature in $N$ time periods, with coupons paid every period can be then written as in Eq.2:

$$A_{i,j}(t_0, T_j) = \sum_{t=0}^{N} \frac{C_{j,t}}{(1+r_j)^t} + \frac{F_j}{(1+r_j)^N}$$

(2)

where

$C_{j,t}$ = coupon expected in period $t$

$F_j$ = face value of the bond

$r_j$ = discount rate for the cash flow

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6 These three time-steps will also be part of the valuation framework for equity and sovereign bonds.

7 Default premia for carbon-intensive companies are likely to increase in the case of moving from a Business-As-Usual scenario to a climate policy scenario, and in particular to the case of a tight climate policy scenario.

8 https://tntcat.iiasa.ac.at/LIMITSDB/dsd?Action=htmlpage&page=about
N = length of the contract.
It is worth reminding that any increase in interest rates, either at the economy wide level or because of an increase in the default risk of $j$, will lower the present value of the stream of expected cash flows and hence the value of the bond. Any decrease in interest rates will have the opposite impact.

**Default premium**
The default premium on the corporate bond is a function of the perceived default risk of the issuer, of the maturity and of the terms of the specific bond, as well as of the probability of the introduction of a climate policy (i.e. related to the carbon-intensity of the company). According to the standard bonds’ evaluation, the bond’s maturity premium is determined by a number of factors including expectations about inflation, investor preferences for liquidity and demands from specific market segments (Gabbi and Sironi 2005, Portes et al. 2001). In line with economic literature, we assume that the default of the issuer $j$ implies a legal procedure and hence a delay in the payments of the recovered assets to the investors. Moreover, bankruptcy costs (Greenwald et al. 1984), e.g. legal costs, loss of assets and social capital, imply that the recovered assets can be significantly smaller in value than the face value of the contract, as reflected by a recovery rate $R_j$ possibly smaller than 1. In this context, a standard way of modeling the corporate bond $i$ of issuer $j$ at the maturity $T_j$ is the expected value:

$$A_{i,j}(t_0,T_j) = p_j(t_0,T_j)R_jF_{ij} + (1 - p_j(t_0,T_j))F_{ij} = F_{ij}(1 - (1 - R_j)p_j(t_0,T_j))$$

(3)

where $\eta_j(T_j)$ is the exogenous stochastic shock hitting the asset side of the issuer, $F_{ij}$ is the face value of the bond (already including $\frac{1}{(1+y)^2}$ as the time-discounting factor), $R_j$ is the recovery rate on the bond contract\(^9\) and $p_j(t_0,T_j)$ is the probability, based on the information available at time $t_0$, that the issuer $j$ defaults on the bond at the maturity $T_j$.

### 3.1.2 Climate policy shocks hitting corporate bonds

In this section, we focus on climate transition risks, which involve technological shocks, policy shocks, and sudden change in climate-financial sentiments that lead to unanticipated adjustments of asset prices.

At time $t^*$ a climate policy shock (e.g. the late and uncoordinated introduction of a carbon tax) is introduced. This affects the economy, which goes from a business-as-usual scenario characterized by no policy $B$ to a scenario $P$, where the market shares of carbon-intensive activities are negatively affected, while the market shares of low-carbon activities are positively affected. We assume that the transition modifies the default probability of

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\(^9\)The recovery rate is a standard notion in banking that indicates the ratio of the amount recovered by the lender upon default of the borrower, for instance after liquidating the collateral associated to the loan contract. Here we consider the recovery rate as exogenous (thus setting the size of potential shocks in a conservative boundary), while maximum losses are obtained with recovery rate equal to 0.
corporate bond’s issuer j through changes in the market share of its economic sector. Conditional to a given climate policy scenario, it follows that a change in default probability of issuer j implies a proportional change in the expected value of the bond at the maturity $T_j$, as from Eq. 4:

$$\Delta A_{i,j}(t_0, T_j, P) = -F_{ij}(1-R_j)\Delta p_j(P)$$  \hspace{1cm} (4)$$

where $\Delta p_j(P)$ denotes the difference of the default probability going from scenario B to P. In our analysis, according to the literature, we consider the current situation in which climate risks have not been yet incorporated into assets prices.

### 3.1.3 Default of the corporate bond’s issuer

The effect of the climate policy shock associated with scenario P is considered by modelling the total assets $\tilde{A}_j(T_j)$ of issuer j at time $T_j$ as a stochastic variable described by Eq. 5:

$$\tilde{A}_j(T_j) = A_j(t_0) + \xi_j(t^*, P) + \eta_j(T_j) \hspace{1cm} (5)$$

where $A_j(t_0)$ is the value of the asset at time $t_0$, $\xi_j(t^*, P)$ is a shock occurring at time $t^*$ associated with the climate policy, and $\eta_j(T_j)$ is the idiosyncratic shock hitting issuers’ operational activities occurring at time $T_j$.

In line with the literature on modeling default events (Battiston et al. 2016) we assume that total liabilities $L_j$ remain constant over time, and that the issuer defaults at time $T_j$ if its net worth $E_j(T_j) = A_j(t_0) - L_j$ at the contract maturity becomes negative as a result of the two shocks, as shown in Eq. 6:

$$E_j(T_j) = A_j(t_0) + \xi_j(t^*, P) + \eta_j(T_j) - L_j = E_j(t_0) + \xi_j(t^*, P) + \eta_j(T_j) < 0 \hspace{1cm} (6)$$

In this formulation, for a given policy shock $\xi_j(t^*, P)$, the conditioned default probability of the issuer is the probability that the idiosyncratic shock $\eta_j$ at time $T_j$ is smaller than a threshold value $\theta_j(P)$, which depends on j’s liability and initial net worth value at time $t_0$, and the magnitude of the climate policy shock $\xi_j$ on its asset side at time $t^*$. The default condition reads:

$$\eta_j(T_j) < \theta_j(P) = -\left(E_j(t_0) + \xi_j(t^*, P)\right) \hspace{1cm} (7)$$

The issuer defaults at the bonds’ maturity $T_j$ if the idiosyncratic shock is lower than the initial value of the bond contract summed to the climate policy shock. In case of no negative policy shock, $\xi_j$ equals 0 and the default condition becomes:

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10 It is also called book equity and defined as total assets minus total liabilities.
\[ \eta_j(T_j) < \theta_j(B) = -E_j(t_0). \]  

Finally, the default probability can be written as:

\[
\mathbb{P}\{\eta_j < \theta_j(P)\} = \int_{\eta_{inf}}^{\theta_j(P)} p(\eta_j) \, d\eta_j
\]

(9)

where \( p(\eta_j) \) is the probability distribution of the idiosyncratic shock \( \eta_j \), and \( \eta_{inf} \) is the lower bound of the support of the probability distribution. The difference in probability as a result of the climate policy shock (i.e. when we move from scenario \( B \) to \( P \)) can be expressed as:

\[
\Delta \mathbb{P} = \int_{\theta_j(B)}^{\theta_j(P)} p(\eta_j) \, d\eta_j.
\]

(10)

### 3.1.4 Profitability and shocks on market share

We now assume that the policy shock impacts the issuer’s balance sheet, and hence the expected value of \( j \)'s corporate bond, via the transmission channel of a change in the market shares of the economic sector of the project, which affects the interest rate and thus the discount factor \( \gamma_j \). We define a market share shock \( u_{S,RE}(P, M, t^*) \) as follows:

\[
u_{S,RE}(P, M, t^*) = \frac{m_{S,RE}(P, M, t^*) - m_{S,RE}(R, M, t^*)}{m_{S,RE}(B, M, t^*)}
\]

(11)

The valuation \( A_{ij}(t_0, T_j) \) of the corporate bond contract can be affected by changes in the economic performance of the economic sector \( S \) where the company operates, and the geographic region \( RE \) of the issuer. Indeed, from a theoretical accounting perspective, under the assumptions of 1) constant demand, 2) constant prices and 3) constant returns to scale, a decrease by \( x \) in the market share of a company translates in a relative decrease \( x \) in its sales and therefore in its profits. Here, we assume that a relative change in the market share of the issuer \( j \)'s sector \( S \) within the geographic region \( RE \), denoted by \( u_{S,RE}(P, M, t^*) \), implies a proportional relative change in the profitability of \( j \)'s. The assumption is justified by a body of empirical literature that confirms strong and positive empirical relation between market-share and profitability (Szymanski ea. 1993). Notice that since the net worth is the integral of profits over one period of time, the relative change in net worth and in profit coincide. Therefore, it is equivalent to assume that a relative change in net worth is proportional to the relative shock in market share:

\[
\frac{\Delta E_j}{E_j} = \beta u_{S,RE}(P, M, t^*)
\]

(12)

where \( \beta \) denotes the elasticity of profitability with respect to the market share. According to the literature, the magnitude of the elasticity coefficient of profitability with respect to
market share for several business sectors is heterogeneous and dependent on several factors, such as firm size. In principle, in our approach, the elasticity coefficient could be estimated empirically for the issuer’s specific sectors and regions.

The trajectories of future values of market shares are taken from the LIMITS database, considering combinations of models $M$ and climate policy scenarios characterized by milder or tighter emissions targets.

For the sake of simplicity, here we assume that the probability distribution $p(\eta_j)$ of the shocks on the issuer’s asset side follows a uniform distribution with support width $\delta$ and mean $\mu$, for a given model $M$, region and sector. In this case, the change in default probability can be expressed as:

$$\Delta \mathbb{P} = \frac{\theta_j(P) - \theta_j(B)}{\delta}$$

(13)

The difference in default threshold is the change in value due to climate policy shock $\xi_j(t^*)$:

$$\Delta \theta_j = \theta_j(P) - \theta_j(B) = -\Delta E_j = -\xi_j$$

(14)

Thus, we have

$$\Delta \theta_j = -\Delta E_j = -E_j \chi u_{S,RE}(P, M, t^*)$$

(15)

and the change in default probability becomes:

$$\Delta \mathbb{P} = -\frac{E_j}{\delta} \chi u_{S,RE}(P, M, t^*)$$

(16)

The idiosyncratic and the climate policy shocks are assumed here to be independent, because at the moment probability distributions of climate policy shocks are yet not available. However, in reality, the two shocks could be interdependent. Indeed, the effect of the climate policy shock is to shift (either left or right) the probability distribution of the idiosyncratic shocks, with positive or negative effects, respectively, for the default probability, for the green or carbon-intensive assets.

We obtain a change in bond’s expected value, conditional to a change from scenario $B$ to $P$:

$$\Delta A_{ij} = F_{ij}(1 - R_j) \frac{E_j}{\delta} \chi u_{S,RE}(P, M, t^*).$$

(17)

Summing over the corporate bonds $j$ in i’s portfolio, we obtain the total change in bond value

$$\sum_j \Delta A_{ij}(t_0, T_j, P) = \sum_j F_{ij}(1 - R_j) \frac{E_j}{\delta} \chi u_{S,RE}(P, M, t^*).$$

(18)
The selection of the parameter values for the application described in this paper is discussed in the Appendix.

3.2 Valuation framework for equity contracts subject to climate policy shocks
We consider the financial actor $i$ (i.e. the central bank)’s investments in equity holdings $E$. For the point of view of investment risk, each equity contract is represented here as a distinct equity issuer $j$, where $j \in E$. We want to develop a valuation framework of OeNB’s equity portfolio able to account for climate policy shocks. The valuation model includes three time-steps consistently with the bonds’ valuation model, i.e.: $t_0, t^*, T_j$, with $t_0 < t^* < T_j$, where $t_0$ denotes the time at which the valuation is carried out, $t^*$ denotes the time at which a climate policy shock potentially occurs, and $T_j$ denotes the final equity value.

We then denote by $A_{i,j}(t_0, T_j)$ the financial valuation at time $t_0$ of $i$ in $j$. Accordingly, the valuation of $i$’s equity portfolio can be written as follows:

$$A_i(t_0) = \sum_j A_{i,j}(t_0)$$ (19)

For the valuation of the equity contract, we rely on the standard approach in the economic literature based on the Net Present Value (NPV), following Gordon’s formulation of future dividends’ flows (Gordon 1959). Dividends are characterized by uncertainty and thus represented as expected value of dividends in our formulation. Given the information available to $i$ at time $t_0$, the equity market price $V_{E}$ at time $t_0$ can be written as:

$$V_{E,t_0} = \frac{D_{iv_1}}{r-g}$$ (20)

where $D_{iv_1}$ is the expected value of dividends at $t_1$, $g$ is the dividends’ growth rate, which is linked to the growth of company’s profits (that are, in turn, linked to the added value of the sector in the economy), and $r$ represents the cost of risk capital for the company.

We set $r - g > 0$ to prevent the well-known singularity of the Gordon’s formula, i.e. that the denominator $r-g$ could become negative or zero.

In a similar way, we can compute the valuation of the equity contract subject to a potential climate policy shock occurring at $t^*$

$$V_{E,t_0} = \frac{D_{iv_1}}{r-g(P)}$$ (21)

where $g(P)$ represents the effect of climate policy shocks on $g$ for energy and electricity sectors and subsectors (fossil fuels and renewable energy). Moving from scenario $B$ to $P$ implies a shock $u_i$ on sector’s market share computed with the LIMITS IAM database, with elasticity $\chi$, so that

$$g(P) - g(B) = \min(0, \chi \cdot u_i)$$ (22)
where $g$ is computed annually, and dividends are paid only if sector’s profits remain positive moving from scenario $B$ to $P$. In a mild (and even more in a stricter) climate policy scenario, we could expect $g^P$ to decrease and even become negative in the case of carbon-intensive sectors. Negative shocks lead to lower profits (and thus lower $g$) for carbon-intensive companies. The opposite effect is expected on companies in renewable energy sectors. Indeed, the introduction of a carbon tax would lead to increase the market-share of renewables in the energy sector and then renewable energy companies’ profits. Thus, the price of equity at $T^*$ accounts for the effect of the climate policy shock on $V_{E,t_0}$ at $t^*$ and for that of an idiosyncratic shock hitting the company, and becomes

$$V_{E,t_0} = \sum_{t=1}^{t^*} D_0 \left( \frac{1+g}{1+r} \right)^t + \sum_{t=(t^*+1)}^{\infty} D_0 \left( \frac{1+g(P)}{1+r} \right)^t$$

(23)

Note that this formulation allows us to consider a scenario characterized by “zero growth” (i.e. when the company simply maintains existing investments). In this case, the equity contract can be considered as a fixed-income product that can be then valued accordingly.

### 3.3 Evaluation of sovereign bonds

Among financial contracts, the evaluation of sovereign bonds subject to climate risk represents the most challenging step for central banks because sovereign bonds usually represent the largest share of their portfolio. The evaluation of sovereign bonds’ risk premia has been associated with macroeconomic and fiscal fundamentals, i.e. actual bond prices react to expected developments in fiscal variables and other macroeconomic variables (Attinasi ea. 2009, Bernot ea. 2004, Costantini ea. 2004). The literature has long established the tight linkage between the outlook of economic growth and fiscal positions because expectation of lower future growth implies additional fiscal adjustment to keep the budget deficit under control (Alesina ea. 1992). Indeed, prolonged low growth trends may rise doubts on public debt sustainability and thus lead to higher risk premia on sovereign bonds, in particular in high-debt countries (Bi 2012). Nevertheless, the relation between climate change, considered as physical or transition risk, and sovereign bonds’ yields and value has not been analysed yet.

In line with this literature, we assume that risk premia on sovereign bonds increases with a decrease in GDP. Further, for the sake of simplicity at this stage of the analysis, we assume a linear negative relation between risk premia and GDP, as follows:

$$\Delta r \sim -\chi \frac{\Delta GDP}{GDP}$$

(24)

where $\chi$ represents the elasticity of bonds’ interest rate (set equal to 1) to changes in GDP growth induced by climate policy shocks. In other words, we are assuming that climate transition risk affects the interest rate through the channel of shocks on macroeconomic
performance and fiscal fundamentals. The bond’s risk-free rate is set equal to 0, and the bond’s maturity is equal to ten (i.e. 10-years bond).

In particular, we consider the relation between sectors’ contribution to GVA and thus to GDP, government’s budget balance and the sustainability of public debt as drivers of bonds’ risk premia. Therefore, climate policy shocks affect the bonds’ risk premia by affecting the GVA of the sectors of economic activity, and thus affecting government’s fiscal revenues. In line with standard evaluations, the value of the sovereign bond $V_{sb}$ can be written as

\[ V_{sb} = \frac{M}{(1+r)^T}, \]  

(25)

where $M$ is the bonds’ notional value, $r$ is the interest rate (i.e. the spread on the sovereign bond $sb$), $T$ is its maturity. We consider the country as a portfolio of financial contracts exposed to specific sectors of economic activity, which contribute to the GVA and GDP, thus to the general taxation and government’s revenue. Thus, the payment of the bond’s coupon at the maturity depends on GDP growth and government fiscal revenues, which must be higher than the cost of interest on public debt. We consider now the introduction of a climate policy shock from the scenario of business-as-usual (B) to a policy scenario P, which hits the market share of the sectors of economic activity $j$ of the domestic economy, computed with the LIMITS IAM. We expect the shock to be negative for fossil fuel extractive, electricity producers and carbon-intensive sectors (e.g. large and sometimes State-Owned energy and utility companies). A negative shock induces a lower GVA of these sectors on GDP and thus to lower tax revenues for the government\textsuperscript{11}.

We can then define

\[ \Delta r = -\chi \frac{\Delta GDP}{GDP} = -\frac{\chi}{GDP} \sum_j \Delta GVA_j = -\frac{\chi}{GDP} \sum_j \frac{\Delta GVA_j}{GVA_j} GVA_j = \]

\[ = -\frac{\chi}{GDP} \sum_j u_j GVA_j \]  

(26).

$\Delta r$ can be interpreted as a spread due to a climate policy shock for a specific country. We call $\Delta r$ the “climate spread”.

In Eq. 26 we assume that relative changes in the gross-value-added of the sector $j$, $\frac{\Delta GVA_j}{GVA_j}$, are proportional to relative changes $u_j$ in the market share of sector $j$, i.e. $u_j = \frac{\Delta GVA_j}{GVA_j}$. If the market has not yet internalized climate risk, we expect the result to be close to zero. In general, shocks may depend on the climate sentiments of the market.

Finally, the change $\Delta r_l$ in the value of sovereign bond rate of sovereign $l$ induces a change in the present-value of the sovereign bond as follows:

\textsuperscript{11} We don’t consider fossil fuel subsidies in our analysis. For an assessment of the impact of climate policies on energy companies benefitting from fossil fuel subsidies, see Monasterolo and Raberto (2018b).
\[ V_{sb} = \frac{F_{sb}}{(1+r+\Delta r)^T} \]  

(27)

### 3.4 Sectors’ market shares trajectories subject to climate policy scenarios

With the aim to assess the impact of climate policy shocks on central banks’ portfolio, we select four climate policy scenarios aligned to the 2°C target from the LIMITS database, and we also consider a baseline of no climate policy (i.e. the Base scenario, Table 1). We use the LIMITS project database (Kriegler et al. 2013) to obtain the market shares trajectories for fossil fuel and renewable energy and electricity sectors and subsectors to which OeNB’s portfolios is exposed. Then, we estimate the effect of the introduction of market-based climate policies (i.e. a carbon tax). The two emissions concentration targets chosen under milder and tighter climate policy scenarios (i.e. 500 and the 450 ppm), determine the amount of CO2 to be emitted in the atmosphere by 2100 consistently with the 2°C aligned IPCC scenarios (IPCC 2014). The 500 and 450 ppm scenarios are associated to a probability of exceeding the 2°C target by 35-59% and 20-41% respectively (Menishausen et al. 2009). Thus, the choice of specific emissions concentration targets could be considered as a proxy for the stringency of the global emission cap imposed by potential climate treaty.

<table>
<thead>
<tr>
<th>Scenario Name</th>
<th>Scenario Class</th>
<th>Target by 2020</th>
<th>Target between 2020 and 2100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base</td>
<td>No climate policy</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td>RefPol-450</td>
<td>Countries Fragmented, Immediate Action</td>
<td>Lenient</td>
<td>450 ppm: 2.8W/m² in 2100, overshoot allowed</td>
</tr>
<tr>
<td>StrPol-450</td>
<td>Countries Fragmented, Immediate Action</td>
<td>Strengthened</td>
<td>450 ppm: 2.8W/m² in 2100, overshoot allowed</td>
</tr>
<tr>
<td>RefPol-500</td>
<td>Countries Fragmented, Immediate Action</td>
<td>Lenient</td>
<td>500 ppm: 3.2W/m² in 2100, overshoot allowed</td>
</tr>
<tr>
<td>StrPol-500</td>
<td>Countries Fragmented, Immediate Action</td>
<td>Strengthened</td>
<td>500 ppm: 3.2W/m² in 2100, overshoot allowed</td>
</tr>
</tbody>
</table>

Table 1: Selected climate policy scenarios from the LIMITS database. Table 1 shows the four climate policy scenarios considered (plus the Base scenario), i.e. RefPol-450, RefPol-500, StrPol-450, StrPol-500.

A change in climate policy implies a change in the sectors’ macroeconomic trajectory, and thus a change in the market share of primary and secondary energy sources. The shock in the market share could differ in sign and magnitude depending on the scenario S, the region RE, the model M used and the sector S. We consider a shock occurring in the period between
2005 and 2050, affecting the market shares of the sectors to which OeNB’s portfolio is exposed via equity, sovereign and corporate bonds.

4. Results

In this section, we focus on the results of the analysis for the sovereign bonds’ portfolio of OeNB, for three reasons. First, sovereign bonds represent the largest share of central banks’ portfolio’s value (including OeNB’s one). Second, sovereign bonds’ value has been affected by the introduction of unconventional monetary policies (e.g. the Quantitative Easing) introduced by several central banks in the aftermath of the last financial crisis and will likely be affected by the return to normal monetary policy regimes. Third, by focusing on sovereign bonds we can introduce the notion of sovereign climate spread and test it empirically. We show here to what extent the transition from a scenario characterised by no climate policy to a milder or tighter climate policy could affect sovereign bonds’ value and yields, via positive and negative shocks, and thus imply gains or losses for OeNB’s portfolio.

For defining the climate spread, we considered that under the climate policy scenarios by 2030, not only the country’s debt/GDP ratio and lower expected economic growth, but also the country’s dependence on fossil fuel energy and electricity, would affect the value of the 10-years sovereign bonds’ spread and sovereign bond’s value. It is worth remarking that in this exercise, the climate policy shocks should be interpreted as potential gains and losses on individual contracts associated to a late and unanticipated transition to climate policy scenarios by 2030.

Table 2 shows the impact of climate policy shocks on the value of sovereign bonds and sovereign bonds’ yields, i.e. the climate spread, computed with two LIMITS’ IAMs, i.e. WITCH and GCAM, under a tighter climate policy scenario (StrPol-450). Notice that positive shocks on the yield correspond to negative shocks on the value of the sovereign bond.

The largest negative shocks on individual sovereign bonds are associated to Australia and Norway, that indeed show the highest yields (i.e. the climate spread). These shocks are led by the large contribution to GVA and thus on country’s GDP of fossil fuel-based primary and secondary energy sources, and by the WITCH IAMs’ forecasted trend of the market share of these specific sectors in a tight climate policy scenario. In contrast, we notice positive shocks for sovereign bonds of countries located in the Baltic region and in Southern Europe. The positive shocks are led by the growing shares of renewable energy sources on the GVA of the energy and electricity sector in those countries, and by the WITCH IAMs’ forecasted trend of the market share of these specific sectors in the StrPol-450 scenario. Interestingly, EU and extra-EU countries where nuclear represents a relevant share of electricity production are subject to positive shocks on sovereign bonds’ value. This is due to the fact that the IAMs used forecast large positive shocks on electricity produced from nuclear sources under all climate policy scenarios.

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12 The results for corporate bonds and equity will be provided in the next version of this working paper.
<table>
<thead>
<tr>
<th>Models’ region</th>
<th>WITCH: bond shock (%)</th>
<th>WITCH: yield shock (%)</th>
<th>GCAM: bond shock (%)</th>
<th>GCAM: yield shock (%)</th>
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<td>-4,04</td>
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*Table 2: Impact of climate policy shocks on the value of sovereign bonds and sovereign bonds’ yields (climate spread) computed with GCAM and WITCH under the tighter climate policy scenario StrPol-450.*
Table 3 shows the magnitude of the climate policy shocks in a milder (i.e. StrPol-500) and tighter (i.e. RefPol-450) scenario, on individual assets of the central bank’s portfolio in percentage points (i.e. 1=1%). The areas highlighted in red (green) show the top five most negative (positive) shocks in the respective climate policy scenarios. For instance, the shock -0.367% on the whole portfolio results from the exposure to a single sovereign bond located outside Europe. In contrast, the most positive shock +0.118, results from the exposure to a single sovereign bond’s issuer located in Europe. These results are influenced by the change in market share of energy and electricity sectors (by fossil fuel or renewable technology) estimated with the WITCH IAM by 2030. The shocks in market shares result in a change in GVA of the sector and thus on country’s GDP. Notice that while the two policy scenarios are relatively close (see Table 1), there are already significant differences in shocks’ values.

<table>
<thead>
<tr>
<th>Model</th>
<th>Scenario</th>
<th>Region</th>
<th>Asset Shock (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>WITCH</td>
<td>LIMITS-RefPol-450</td>
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<tr>
<td>WITCH</td>
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<td>WITCH</td>
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<td>WITCH</td>
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<td>-0.127</td>
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<td>WITCH</td>
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<td>EUROPE</td>
<td>0.118</td>
</tr>
</tbody>
</table>

Table 3: Magnitude of the climate policy shocks on individual sovereign bonds in a milder (i.e. StrPol-500) and tighter (i.e. RefPol-450) scenario by region.

5. Conclusions and policy recommendations
In this paper, we propose the first carbon risk assessment methodology for equity, sovereign and corporate bonds’ contracts exposed to shocks led by the late and sudden transition by 2030. Our approach builds on the first climate stress-test methodology developed by Battiston ea. (2017) and further refined in Monasterolo ea. (2018). The carbon risk assessment methodology is then applied to OeNB’s portfolio, and we present here the results
for sovereign bonds. The innovativeness of our manuscript is threefold and consists of: i) the formalization of a model that allows to price climate transition risks into specific types of assets included in central banks’ portfolios, ii) the introduction of the notion of climate spread on 10-years sovereign bonds and its empirical assessment, iii) the computation of overall gains or losses for an investor’s portfolio under mild or tight climate policy scenarios, by country and sector of economic activity. To our knowledge, this is the first time that a carbon risk assessment methodology for central banks’ portfolios is developed and applied through a joint collaboration between research and central banks.

Mainstreaming portfolios’ carbon risk assessment for central banks is then fundamental for three reasons. First, it allows central banks to identify the asset classes and investors who are vulnerable yet relevant to climate risks, and the risk transmission channels involved. Second, it allows them to assess their own portfolio’s exposure to climate risks and the potential losses or gains which it could experience. Third, it allows central banks to foster the alignment of the financial sector to sustainability, through the market signaling effects of their monetary policy tools, including green assets purchase programs.

Our methodology is modular, transparent and thus can be replicated on (or tailored to) other central banks and investors’ portfolios. First, we have estimated the impact of the climate policy shocks by 2030 on the market shares’ trajectories of energy and electricity sectors based on fossil fuel and renewable energy technologies per each country of exposure of OeNB’s portfolio, using the LIMITS IAMs. We have considered climate policy shocks induced by a late and sudden transition from a Business as Usual scenario characterized by no climate policy to scenarios characterized by the introduction of either mild (i.e. 500 ppm) or tight (450 ppm) climate policies (represented by a carbon tax) by 2030. Then, we have estimated the transmission of the climate policy shock on the sectors’ market share into a change in the value of assets, i.e. corporate bonds, equity, sovereign bonds that compose OeNB’s portfolio. For each asset, we have developed an analytical formalization to assess the change in individual contract’s value conditioned to a climate policy shock, and to derive the estimate of the change in overall portfolio’s value. In particular, the shock on sovereign bonds value is computed based on a newly developed metric, i.e. the climate spread. Finally, we have discussed the results in terms of gains or losses for OeNB’s sovereign bonds’ portfolio, identifying the main drivers of impacts.

Our analysis suggests that a mismanaged and uncoordinated introduction of climate policies, and investors’ inability to anticipate climate transition risks, could affect in a relevant and negative way the value of sovereign bonds in countries where revenues from economic activities and GDP growth are still carbon-intensive. In these countries, the climate spread for a 10-years sovereign bonds reaches the highest level. This, in turn, could translate into losses for central banks owning them. In contrast, positive shocks on sovereign bonds’ values are associated to countries with growing shares of renewable energy sources on the GVA of the energy and electricity sector, and thus to negative shocks on yields. The climate spread thus crucially influences gains or losses for the central bank’s portfolio.
Some final remarks apply. First, it would be tempting to think that shocks are rather small in percentage points. However, it is worth remarking that the climate policy shocks scenarios considered are mid-term (i.e. at 2030). In addition, it is not unlikely that tighter climate policy scenarios than the ones used in this analysis might have to be considered (and thus tighter climate policies introduced before 2030) to limit global temperature increase below 2°C by 2100, since global CO2 emissions are still increasing (NOAA 2018, Steffen et al. 2018). Then, it is well-known that even few decimal points of expected change in GDP growth could have a remarkable effect on sovereign bonds’ yields due to markets’ expectations and sentiments, as shown by recent events in the euro-area countries. Further, at the light of the deep uncertainty on the introduction of coordinated climate policies by UN governments vis-à-vis the evidence of global CO2 emissions increase, our results should be considered as conservative.

In conclusion, our methodology and results are relevant for central banks who are concerned about the financial implications of climate risks but still lack standardized tools to mainstream climate transition risk in the financial evaluation of their and of investors’ portfolio. Metrics for carbon risk assessment of financial contracts are crucial to support central banks in the evaluation of investors portfolios’ exposures to climate risks and in their understanding of the conditions for the onset of climate-related financial risk, and thus in their strategic decisions on how to tame such risks. Current developments of this work include the application of the methodology to assess the price change in OeNB’s equity and corporate bonds’ exposures under climate policy scenarios at 2030.

References


