The Climate Spread of Corporate and Sovereign Bonds

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Abstract

Climate risk brings about a new type of financial risk that standard approaches to risk management are not adequate to handle. We develop a model that allows to compute the valuation adjustment of corporate and sovereign bonds conditioned to climate transition risk, based on available forward-looking knowledge on climate policy scenarios provided by climate economic models. We investigate the impact of the endogeneity and deep uncertainty of future scenarios on both the valuation of individual bonds and on standard risk metrics for a leveraged investor, considering the role of fossil fuels and carbon intensive activities in the economy of countries. We demonstrate that an investor's Value at Risk and Expected Shortfall have low sensitivity to key parameters such as the Probability of Default (PD) of the bond In contrast, the investor's PD is very sensitive to these parameters, and increases with the PD of the bond and with the probability of occurrence of the adverse climate transition scenario. Choosing the wrong scenario could lead to a massive underestimation of losses. Thus, Climate stress test exercises should allow for a wide enough sets of scenarios to avoid underestimation of losses. We apply the methodology to the Austrian National Bank's portfolio of sovereign bonds. In carbon intensive countries, the cost of climate misalignment is reflected in a higher Climate Spread and affects sovereign risk and portfolio's performance. These results have important implications for the selection of relevant climate transition scenarios in climate stress-testing exercises, and for the assessment of climate-related financial risk for supervisory and prudential policy purposes.

Keywords: climate transition risk, financial stability, financial pricing models, deep uncertainty, sovereign bonds, climate spread, central bank's portfolio, OECD countries.

1. Introduction

It is increasingly recognized academics, by central banks and financial regulators that the transition to a low-carbon economy could be disorderly, i.e., characterised by policy and technology shocks that cannot be fully anticipated by investors, what is usually referred to as climate transition risk (Battiston et al. 2017, NGFS 2019, Bolton et al. 2020). In this context, carbon-intensive (low-carbon) firms would face unanticipated negative (positive) shocks in their costs, profitability and market share. In particular, the performance of fossil fuels and carbon intensive firms would shrink, giving rise to carbon stranded assets (Caldecott 2018, van der Ploeg and Rezai 2020). The shock can be transmitted to the value of the financial contracts (e.g. bonds) and affect the value of the portfolios of investors who hold them (Stolbova et al. 2018). If large and correlated asset classes are involved, implications for asset price volatility and financial instability could occur (Monasterolo et al. 2017). Recently, central banks and financial regulators referred to this scenario talking about Climate Minsky Moments (NGFS 2018) and Green Swans (Bolton ea 2020). Their concerns are based on a stream of research on climate financial risk assessment and climate stress-testing.

The climate stress-test by Battiston et al. (2017) showed that contracts at risk of becoming stranded represent a large share of investors' portfolios, reaching 43 % of the equity holdings of investment funds and pension funds in the EU and US. In addition, the losses

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could be amplified by the interconnectedness of financial actors (Battiston et al. 2012, Billio et al. 2012) and complexity of financial networks (Battiston et al. 2016) that reverberate risk.

In this context, pricing forward-looking climate transition risk in the value of contracts and in investors' portfolios is fundamental to inform investors' risk management strategies and financial regulation aimed to preserve financial stability.Nevertheless, the characteristics of climate risk, i.e. forward looking, deep uncertainty, non-linearity and endogeneity, make traditional approaches to financial valuation inadequate. In particular, financial pricing and stress-testing based on backward-looking information, average scenario values and normal distributions of shocks could lead to underestimate risks.

We contribute to fill this knowledge gap by developing a model that allows to compute the valuation adjustment of corporate and sovereign bonds, and standard financial risk metrics for a leveraged investor (e.g. Value-at-Risk (VaR), Expected Shortfall (ES)), conditioned to forward-looking climate transition risk scenarios. These are based on available forward-looking knowledge on climate policy scenarios provided by climate economic models (i.e. Integrated Assessment Models (IAMs) reviewed by the IPCC report.

Our model allows to investigate the impact of the endogeneity and deep uncertainty of climate scenarios on both the valuation of individual bonds (corporate and sovereign) and on portfolio's performance. First, we calculate the shock on the output and market share of economic activities characterised by a specific energy technology (e.g. fossil fuel or renewable) conditioned forward-looking climate transition risk scenarios characterised by the introduction of a science-based carbon tax. Then, we introduce the shock in the Probability of Default (PD) q of the bond, and the effects in the bond value and yield (i.e. the Climate Spread). Third, we demonstrate the relation between q, the PD of the portfolio of a leveraged investor, and the Climate VaR and ES of her portfolio conditioned to different values of correlation and climate transition scenarios. Then, we consider the case in which the probability of default on q conditioned to the climate transition scenario is endogenous and characterised by deep uncertainty, and the impact on the PD of the portfolio. In particular, we show that an investor's VaR and ES have low sensitivity to key parameters such as the PD and Loss Given Default of the bonds in the portfolio, and scenario probability. In contrast, the PD of investors' portfolio is very sensitive to these drivers, and the effect can be stronger when the probability of occurrence of the climate scenario are endogenous. In particular, PD increases with q and with the probability of the adverse climate transition scenario.

Finally, we apply the methodology to the portfolio of sovereign bonds issued by OECD countries and included in the Austrian National Bank (OeNB)'s non-monetary policy portfolio.

This preliminary and work in progress version of the manuscript is organized as follows. Section 2 discusses the nature of climate risk that investors should consider. Section 3 introduces the information set of a risk averse investor who aims to assess forward-looking climate transition risk in her portfolio of bonds. Section 4 provides the demonstrations of the sensitivity of the PD of the portfolio and its Climate VaR ans ES to q in the case of exogenous and endogenous probability of occurrence of scenarios. Section 5 discusses the application of the climate financial risk pricing model to the sovereign bonds' portfolio of OeNB and section 6 concludes.

2. Climate change: a new type of risk for finance

In 2015, Mark Carney, the former Governor of Bank of England, in his speech about The tragedy of the horizons at Lloyds, introduced climate change as a new type of risk that could affect investors' portfolios. In particular, he highlighted three channels through which climate change could impact activities in the economy and finance, i.e. physical risk, transition risk and liability risk (Carney 2015). It is now recognized that while climate physical risks will be more visible in the medium-to-long term, climate transition risks could happen earlier and be more financially relevant (NGFS 2019). Since then, central banks and financial regulators' attention of climate-related financial risks increased, and with that, the awareness of the need for dlsclosing and assessing such risks.

2.1. Characteristics of climate risk

The characteristics of climate change make it a new type of risk for investors, and challenge the usability of traditional financial pricing (for a comprehensive review, see Monasterolo 2020), and include:

- Forward-looking dimension. The impacts of climate change is on the time scale of two decades or longer1. However, the time horizon of financial markets is much shorter. Investors' decisions follow a much shorter time horizon (e.g. three months for fund managers) and are based on a market benchmark (performance) that is backward-looking because estimated on past companies' performance.
- Non-linearity. The probability of forward-looking climate shocks can't be inferred from historical data being non-linear in nature and not normally distributed. For instance, Ackerman (2017) found that the 2003 Western European summer was 5.4 above mean temperature for 1864-2000. A similar heat-wave occurred in Eastern Europe in 2010. If such events happen every 7 years, we cannot assume that temperatures changes are normally distributed.
- Deep uncertainties On the one hand, the deepest climate-related shocks are expected to occur in the mid-to long-term, but their exact localization and magnitude is unknown today. This is due to the nature of the earth system and leads to the presence of tail events (Weitzman 2009), tipping points and domino effects (Steffen et al. 2018), which are associated to large uncertainty (Kriegler et al. 2009). Tipping points increase the urgency and the magnitude of the climate policies to be introduced (Lenton et al. 2019), as well as the cost of inaction for future generations (Lemoine and Traeger 2016). On the other hand, costs and benefits estimates of action (as well as the cost of inaction) vary substantially across climate scenarios with the assumptions on agents' utility function, future productivity growth rate, and inter-temporal discount rate (Stern 2008; Pyndick 2013).

- Complexity. The likelihood of the realization of a given climate scenario pathway depends on the ability of countries to introduce coordinated climate policies, and on the fact that socio-economic agents will react rationally by changing their consumption and production behaviour. But since agents often take decisions departing from rational expectations and behaviors, the aggregate effect of heterogenous agents' behavior can give rise to emerging system's properties that cannot be deducted from the simple sum of individual behaviours (Dosi and Roventini 2019). These properties generate complexity in understanding the system's response to shocks, which can be endogenously generated (Farmer et al. 2015, Battiston et al. 2016), requiring us to think in terms of complex adaptive systems (Lamperti et al. 2018).

- Endogeneity and circularity of climate risk. The likelihood of achieving the global climate targets depends way climate policies are introduced. Uncertainty of climate policies affects investors' expectations on the financial risk deriving from the very same policies, and thus their investment decision. This generates the possibility of multiple equilibria, a situation where a rational agent cannot identify a preferred investment strategy in the low-carbon transition (Battiston et al. 2017; Battiston and Monasterolo 2018).

Further, research developed following the Great Financial Crisis highlighted the key role of financial complexity and financial actors' interconnectedness in amplifying shocks via the reverberation of losses within the financial network (Battiston et al. 2012, 2016) and in contributing to the building up of systemic risk (Battiston et al. 2012, Billio et al. 2012, Tobias and Brunnermeier 2016).

These characteristics introduce new challenges for financial risk pricing that builds on the identification of the most likely scenarios, consider normal distribution of shocks, complete markets and lack of arbitrage. The computation of the expected values and the estimation of financial risk metrics (e.g. volatility) are backward looking in nature because they rely on historical values of market prices.

Failing to consider climate risk could have long-lasting consequences for the investor in the low-carbon transition. On the one hand, if the shock is not anticipated, investors would not change their portfolios' allocations (e.g. by decreasing their exposure to carbon-intensive assets and increasing their exposures to low-carbon assets). In this context, since asset managers take investment decisions based on the benchmark in their respective markets (Greenwald and Stiglitz 1986), the market benchmark remains carbon-intensive, leading to the potential realization of carbon stranded assets in the economy and finance. Recent research shows that the market benchmark is carbon intensive, as in the case of corporate bonds market benchmark and the European Central Bank's corporate bonds purchase (CSPP) (Battiston and Monasterolo 2019). On the other hand, the assessment of the policy shock could be incorrect even on average across market participants, as shown by several recent policy events (achievement of Paris Agreement, the US withdrawal from Paris Agreement, the outcome of 2018 Italian elections). These have been incorrectly forecast by most observers and investors but are having severe long-term effects on the financial conditions of a country.

2.2. Climate-financial decision theory under deep uncertainty

A first challenge for introducing climate into financial risk evaluation is related to the treatment of the deep uncertainty that characterizes climate change (Hallegatte et al. 2012). Indeed, (largest) climate shocks are expected to occur in the long-term (i.e. after 2050, IPCC 2014) but their exact localization, timing and magnitude (also in terms of economic and financial losses) are unknown (Weitzman 2009). In addition, since climate shocks are expected to be non-linear, their probability distribution cannot be inferred from historical data, and neither can be approximated by a normal distribution (Ackerman 2017). This means that the losses associated to future climate shocks cannot be extrapolated from the past, and so is the performance of the assets exposed to those shocks. However, in traditional financial pricing models (e.g. Merton 1974 for corporate debt) shocks follow a normal distribution, are thus risk is calculated via measures of volatility (e.g. beta, Sharpe 1964). Then, in absence of mitigation measures, climate shocks could trigger tipping points (Vaks et al. 2013), beyond which the elements of a systems could change in a potentially irreversible way (Solomon et al. 2009; Steffen et al. 2018), leading to domino effects.

Another source of uncertainty is related to policy makers and financial actors' reactions to future climate shocks. First, the decision of individual governments to implement climate policies coherent with their Nationally Determined Contributions (NDCs) depends both from internal political factors (citizens' support, economic growth path, financial stability) and from their expectations towards other governments' actions. Then, the announcement of a government to introduce a specific climate policy may trigger an investor's reaction, which depends on the investor's expectations about the credibility of the policy, i.e. her *climate sentiments* (see Dunz et al. 2019 for a review). If investors trust the government, they would react to that by revising their portfolio's allocation by increasing (decreasing) their exposure to low-carbon (high-carbon) assets. However, if large asset classes and large financial actors (in terms of market share) are involved, and if the reaction takes place in a short time frame, the effect would most likely be assets' prices volatility.

Traditional climate economics and financial models miss this circularity (Battiston and Monasterolo 2018) overlooking the conditions for endogenously generated drivers or barriers to the success of climate policies to emerge. Overall, the relation between policy decisions and investors' expectations on financial risk deriving from the policies generates the possibility of multiple equilibria. Therefore, simple political and game theory considerations could not exclude the endogeneity of default conditions, such as the decision of a government not to align to the climate targets now and to run the risk of default later. This decision may be rational for some governments under specific conditions (e.g. when short-term costs of alignment are high, see e.g. Poland). It is well known that the computation of probability distributions of shocks is not possible under multiple equilibria. Thus, a traditional VaR strategy can't be pursued, and no preferable risk investment for investors could be identified. It follows that the standard approach to financial risk analysis, where most likely scenario are identified, expected values computed, and financial risk estimated based on backward looking metrics and historical values of market prices, is not adequate in this context (Battiston 2019).

Recent literature has applied decision making under uncertainty to the analysis of the optimal climate policy. On the one hand, Drouet et al. (2015) focus on the choice of the decision-making criteria (e.g. maximum expected utility versus maxmin expected utility). On the other hand, Berger et al. (2017) analyse risk aversion towards model uncertainty.

3. Model

We present here the conceptual and analytical blocks of the framework for climate-financial risk assessment under uncertainty.

3.1. Information set of a risk averse investor

We consider a risk averse investor that aims to assess the exposure of her portfolio to forward-looking climate transition risk, provided by the IAM scenarios, in a context of possible incomplete information, incomplete markets and deep uncertainty (Keynes 1973, Knight 1921, Greenwald and Stiglitz 1986, Nalebuff and Stiglitz 1983).

The information set of the risk averse investor includes:

- The current available knowledge about climate transition risk that can affect the investment value, using the climate policy scenarios developed by the international scientific community and reviewed by the Intergovernmental Panel on Climate Change (IPCC).
- The information on the scenarios conditioned shocks on sectors of economic activities developed by climate economic models. We want to focus in particular on the subset of models in which the economic output is computed consistently with the Greenhouse Gases (GHG) emission targets and with a feedback loop from climate impact to economic output.
- The time horizons that is relevant both for investment strategies and for the low-carbon transition, ideally from 2020 to 2050 (possibly up to 2100).
- The varying level of investor's risk aversion preferences, to go beyond the notion of "most likely scenario" and to include the notion of set of "worst case scenarios".

Then, we can define the information set of investors consisting of the following elements:

- A set of *Climate Policy Scenarios* P_l corresponding to GHG emission reduction target across regions:

$$\textbf{ClimPolScen} = \{B, P_1, ..., P_l, ..., P_{n^{\text{Scen}}}\} \tag{1}$$

  This notion formalizes the climate scenarios identified by the scientific and policy community (IPCC). B denotes the Business-as-Usual scenario.

- A set of *economic output trajectories* for each country j, sector S under each scenario P_l, estimated with a climate economic model M_m

$$\textbf{EconScen} = \{Y_{1,1,1,1}, ..., Y_{j,S,P_l,M_m,...}\} \tag{2}$$

  This notion formalises the quantitative knowledge produced by existing climate economic models (including the classes of IAMs).

- A set of forward-looking *Climate Policy Shock Scenarios*, indicating a disorderly transition from $B \rightarrow P_l$. The shock is obtained as differences in sectors' output between B and the climate policy shock trajectories P_l for the same model M_m, and can be calculated either across trajectories or across years (2020 to 2100) within the same trajectory:

$$\textbf{TranScen} = \{B \rightarrow P_1, ..., B \rightarrow P_l, ..., B \rightarrow P_{n^{\text{Scen}}}\} \tag{3}$$

- A set of *Climate Policy Shocks* on economic output for j, S under transition scenario estimated with model M_m

$$\textbf{EconShock} = \{..., \frac{Y_{j,S,P_l,M_m} - Y_{j,S,B,M_m}}{Y_{j,S,B,M_m}}, ...\} \tag{4}$$

3.2. Composition of the economy

We consider n countries j whose economy is composed of m economic sectors S. Economic activities included in S are based on a refined classification of the Climate Policy Relevant Sectors (CPRS) originally introduced in Battiston et al. (2017) These are economic activities that could be affected positively or negatively in a disorderly low-carbon transition, i.e., they are relevant for assessing climate transition risk. As such, they allow to consider the economic and financial risk stemming from the (mis)alignment to the climate and decarbonization targets of firms and sectors (recorded at the NACE 4-digit level) that contribute to the Gross Value Added (GVA). CPRS include fossil fuel, utility, energy intensive, buildings, transportation, agriculture, identified considering (i) the direct and indirect contribution to GHG emissions; (ii) their relevance for climate policy implementation (i.e. their costs sensitivity to climate policy change, e.g. the EU carbon leakage directive 2003/87/EC); (iii) their role in the energy value chain; (iv) the firms' future investment plan (e.g. CAPEX). This allows to add a climate risk connotation to the NACE 4-digit sector classification that per se' is not able to provide any proxy of climate risk, not carrying any info on the technology mix nor on the relevance for climate policy implementation and future firms' plans. The CPRS allows then to overcome the limits of pure classification of exposures based on GHG emissions and NACE 4-digit sectors. More recently, the classification has been revised (CPRS 2019) to provide a more granular classification of the economic activities in terms of technologies (utility—electricity—wind, solar, gas). The CPRS classification was used by the European Central Bank (2019) and by the European Insurance and Occupational Pension Authority (EIOPA, Battiston et al. 2019a) to assess financial actors' exposure to climate transition risks in the EU.

Within S, we focus on the fossil fuel and renewable energy primary and secondary sectors and sub-sectors, due to the main role thy play in the low-carbon transition via the energy and electricity supply along the value chain. Firms that compose economic sectors S are considered as a portfolio of cash flows from fossil fuel and renewable energy activities. The classification of countries and regions affected by the climate shock is based on the LIMITS/CD-LINKS aggregation, see Kriegler et al. (2013), McCollum et al. (2018).

In particular, we can define a set of issuers $\{1, ..., j, ...n\}$ from economic sectors $\{1, ..., s, ..., n^{\text{Sect}}\}$, where the issuers' GVA in a country is the sum of sectors' contributions: $\text{GVA}_j = \sum_s \text{GVA}_{j,s}$

CPRS 2017	CPRS 2019
1-fossil	1-fossil|coal
	1-fossil|oil
	1-fossil|gas
2-utility	2-utility|electricity|coal
	2-utility|electricity|gas
	2-utility|electricity|solar
	2-utility|electricity|wind
	2-utility|electricity|biomass
	2-utility|electricity|marine
	2-utility|electricity|nuclear
	2-utility|other
	2-utility|water&sewerage
	2-utility|waste
3-energy-intensive	3-energy-intensive

Figure 1: Climate Policy Relevant Sectors. The figure shows the classification of economic activities by different degrees of granularity by energy technology source.

3.3. Disorderly transition and its impact on economic activities

We consider the contribution of issuer j's to the sector S's GVA and fiscal assets and how this can be affected by changes in its economic performance, either negatively or positively. We then relate the performance of the economic activity to the change in its market share as a result of a disorderly climate policy transition scenario.

Then, we introduce the climate transition scenarios. The transition to a low-carbon economy could occur orderly or disorderly. Orderly means that the climate policies (e.g. a carbon tax) for decarbonizing the economy and achieving the climate targets are introduced early and in a coordinated way among countries. In this scenario, investors are able to anticipate the climate policy introduction and price it in their risk management strategies. In contrast, if climate policies are introduced in a sudden way with regard to the decarbonization targets (e.g. EU2030 climate and energy targets), they could trigger a disorderly response from investors who may not able to anticipate (and thus price) the policies in their investment strategies. In this context, carbon-intensive (low-carbon) firms would face unanticipated negative (positive) shocks. Thus, the performance of issuers in sector S is affected via a change in economic activities' market share, cash flows and profitability. The transition scenario that will realize is uncertain and largely endogenous, as it depends from governments' chosen path for the introduction of climate policies, and investors' reaction. In these conditions, we need to depart from the idea of "most likely/feasible scenario" and consider sets of several scenarios to be able to determine how wrong could an investor be in computing the largest losses of her portfolio. The disorderly transition affects the GVA of the sectors. Negative shocks result from the climate policy shock on the GVA of sectors that rely on fossil fuels technologies (e.g. coal, oil, gas), while positive shocks result from the impact on the GVA of sectors that rely on renewable energy technologies (e.g. solar, wind). The climate policy shock is calculated at the sector level, using IAMs.

The disorderly transition is thus intended as a temporary out-of-equilibrium shift of the economy between two separate equilibrium trajectories based on the energy technology that drives the transition.

Then, we consider macroeconomic trajectories of output over time for sector S consistent with climate policy scenario $P \in \{..., P^{\mathrm{RefPol}}, P^{450}, ...\}$ The **Climate Policy Shock Scenario** consists in the transition from a trajectory B to a trajectory P. Taking as an example the GVA of the following CPRS, we have:

- primary energy fossil (**PrFos**)
- electricity fossil (**ElFos**) / renewable (**ElRen**)

$$u_j^{\mathrm{GVA}}(P) = u_{j,\mathrm{PrFos}}^{\mathrm{GVA}}(P)\, w_{j,\mathrm{PrFos}}^{\mathrm{GVA}}(B))+$$
$$u_{j,\mathrm{ElFos}}^{\mathrm{GVA}}(P)\, w_{j,\mathrm{ElFos}}^{\mathrm{GVA}}(B)) + u_{j,\mathrm{ElRen}}^{\mathrm{GVA}}(P)\, w_{j,\mathrm{ElRen}}^{\mathrm{GVA}}(B))$$

We assume that a % shock on output $\approx$ % shock on GVA, u_j^{GVA}, for each sector of j

$$u_j^{\mathrm{GVA}}(P) = \frac{\mathrm{GVA}_j(P) - \mathrm{GVA}_j(B)}{\mathrm{GVA}_j(B)} = \sum_s \left(\frac{\mathrm{GVA}_{j,S}(P) - \mathrm{GVA}_{j,s}(B)}{\mathrm{GVA}_{j,S}(B)} \quad \frac{\mathrm{GVA}_{j,S}(B)}{\mathrm{GVA}_j(B)}\right)$$
$$u_j^{\mathrm{GVA}}(P) = \sum_S (u_{j,S}^{\mathrm{GVA}}(P) \quad w_{j,S}^{\mathrm{GVA}}(B))$$

where then $u_{j,S}^{\mathrm{GVA}}(P)$: GVA shock on sector s; $w_{j,S}^{\mathrm{GVA}}(B)$: share of GVA of sector S

From an accounting perspective, at the level of an individual firm, it holds true that a decrease (increase) x in the market share translates in a relative decrease (increase) x in its sales, as long as market conditions are the same[1]. A body of empirical literature has found a strong and positive relation between firms' market-share and profitability (Szymanski et al. 1993; Venkatraman et al. 1990). At similar argument can be made at the level of countries' sectors, such as their utility sectors. A decrease (increase) x in the market share in a given region of countries competing on the energy market translates in a relative decrease (increase) x in its sales. As a result, there is a decrease (increase) in the tax revenues that the sovereign issuer j collects from the firms operating in that sector in the country.[2] In the case of the energy and utility sectors, this argument is corroborated by the fact that ownership is very concentrated in both fossil and renewable business. Indeed, in most EU countries there is just a major energy firm (e.g. OMV in Austria, ENI in Italy) and one major utility firm.

The net effect on the profit of a given sector depends on its pre- and post-shock energy technology mix. For instance, sector S_{j_1} will have a larger post-shock profit compared to S_{j_2}, denoted as $\pi(S_{j_1}, P) > \pi(S_{j_2}, P)$, because it starts from a larger pre-shock share of renewable-based power (everything else being equal). Moreover, S_{j_2}'s profit (summed over the two business lines) could decrease after the policy shock, denoted as $\pi(S_{j_2}, P) < \pi(S_{j_2}, B)$, if it is not possible for S_{j_2} to more than compensate on the renewable business line the losses on the fossil business line.

The final impact of the climate policy shock on the net fiscal assets of an issuer j depends not only on the tax revenues from sector S_j and thus on its profit $\pi(S_j, P)$, but also on the expenses that the issuer incurs (e.g. welfare, debt repayment, public investments). If we consider j as a sovereign issuer, we can assume that a relative change in the market share of sector S within the country j, implies a proportional relative change in the net fiscal assets of issuer j from sector S.

[1] More precisely, it holds under the conditions that total demand and prices remain unchanged in the period considered, and that returns to scale are constant

[2] Notice that while the tax rate may vary in principle with firms' size (e.g. total level of pre-tax profits), in many cases large firms are subject to similar tax rates than smaller firms. Hence, agents assume that an $x\%$ drop in firm's profits implies the same $x\%$ drop in revenues.

In the case of a sovereign issuer, we define the *net fiscal assets related to sector* S, denoted as $A_j(S)$, as the difference between accrued fiscal revenues from sector S and public investments and subsidies granted by j to the same sector.

The impact of the market share shock (resulting from the policy shock P) on net fiscal assets of sector S is thus assumed to imply a change $\Delta A_j(S,P,M)$, estimated under model M, as follows:

$$\frac{\Delta A_j(S,P,M)}{A_j(S)} = \chi_S \, u_j(S,P,M),$$

where χ denotes the elasticity of profitability with respect to the market share.

The forward-looking trajectories of sectors' market shares are taken from the LIMITS scenario database (Kriegler ea. 2013), considering combinations of IAM M and four climate policy scenarios P, characterized by different GHG emissions targets and way to achieve them [3].

Because, in general, the policy shock affects at the same time several sectors in the economy of the issuer j, we have to consider the total net effect on the issuer's net fiscal assets as follows:

$$\frac{\Delta A_j(P,M)}{A_j} = \sum_S \frac{\Delta A_j(S,P,M)}{A_j(S)} \frac{A_j(S)}{A_j} = \sum_S \chi_S \, u_j(S,P,M) \frac{A_j(S)}{A_j},$$

The elasticity coefficient could be estimated empirically for the specific sectors of activity of the bond issuers. However, in the context of transition risk, the shock is going to be forward-looking (we do not dispose of past examples of disorderly low-carbon transition). Thus, in the empirical analysis in section 5 we have assumed a value of χ constant and equal to 1 (typical empirical values range between 0.2 and 0.6).

3.4. Model for corporate bonds valuation

We develop here a model for counterparty valuation in the case of corporate and of sovereign bonds issuer, defining the default condition and the default probability for the

[3] See the LIMITS database documentation for more details https://tntcat.iiasa.ac.at/LIMITSDB/static/download/LIMITS_overview_SOM_Study_Protocol_Final.pdf

bonds. We consider a risky (defaultable) bond of corporate issuer j, issued at t_0 with maturity T. The bond value at time T, with bond *Recovery Rate* R (i.e. % of notional recovered upon default), and *Loss-Given-Default* LGD (i.e. % loss) can be defined as:

$$v_j(T) = \begin{cases} R_j = (1 - \mathrm{LGD}_j) & \text{if j defaults (with prob. } q_j) \\ 1 & \text{else (with prob. } 1 - q_j). \end{cases} \tag{5}$$

The expected value of bond's payoff can then be written as:

$$\mathbb{E}[v_j] = (1 - q_j) + q_j\, R_j = 1 - q_j\,(1 - R_j) = 1 - q_j\, \mathrm{LGD}_j. \tag{6}$$

The bond price v_j^* is equal to the bond discounted expected value, with y_f risk-free rate. The price defines implicitly the yield y_j of bond j (under the risk neutral measure) as follows:

$$v_j^* = e^{-y_f\, T}\, \mathbb{E}[v_j] = e^{-y_f\, T}\,(1 - q_j \mathrm{LGD}_j) = e^{-y_j\, T}. \tag{7}$$

Finally, the bond spread is defined as:

$$s_j = y_j - y_f, \tag{8}$$

with $e^{-s_j\, T} = 1 - q_j\, \mathrm{LGD}_j$. A useful fact about spread is that:

$$s_j \approx \frac{1}{T}\, q_j(1 - R_j) = \frac{1}{T}\, q_j\, \mathrm{LGD}_j \text{ (for small } s_j). \tag{9}$$

3.5. Corporate bond default conditions

The value of the assets in the corporate bond issuer j's balance sheet are denoted as $A_j(t_0)$, $A_j(T)$, with t_0 being the time of issuance and T the maturity. The liabilities are considered constant and denoted as $L_j(T)$. Following Merton (1974), the default condition reads as:

$$A_j(T) = A_j(t_0)(1 + \eta_j(T)) < L_j(T), \tag{10}$$

with $\eta_j(T) \in \mathbb{R}$ denoting the idiosyncratic shock (e.g. on firm j productivity), $\phi(\eta_1, ..., \eta_j, \eta_n)$ denoting the joint probability distribution (accounting for possibly correlated across shocks).

We add the climate policy shock denoted by ξ_j on j's assets, which causes an adjustment in the issuer's PD. The shock ξ_j can be regarded as a shift (left/right) in the distribution of the idiosyncratic shock η_j and a "jump" up/down in the PD. We define the new default condition as:

$$A_j(T) = A_j(t_0)(1 + \eta_j(T) + \xi_j(P)) < L_j(T) \tag{11}$$

$$\iff \eta_j(T) \leq \theta_j(P) = L_j(T)/A_j(t_0) - 1 - \xi_j(T, P), \tag{12}$$

with $\theta_j(P)$ denoting the default threshold under the scenario P. The climate policy shock $\xi_j(P)$ can be either positive or negative (given the composition of j: $\xi_j(P) > -1$), and possibly correlated across issuers index j.

The default conditions could be interpreted also in the context of sovereign risk. In particular, following a stream of literature (Gray et al. 2007), we can model the payoff ofthe defaultable sovereign bond as dependent on the ability of the sovereign to repay the debt out of its fiscal revenues accrued until the maturity, by revising Eq.14.

3.6. Corporate default probability

The default probability $q_j(P)$ of issuer j, under Climate Policy Scenario P, is defined as follows:

$$q_j(P) = \mathcal{P}(\eta_j < \theta_j(P)) = \int_{\eta_{\inf}}^{\theta_j(P)} \phi_P(\eta_j)\, d\eta_j, \tag{13}$$

with $\phi_P(\eta_j)$ being the probability distribution of the idiosyncratic shock η_j, and $\eta_{\inf}$ the lower bound of distribution support.

Frequent small productivity shocks across time and firms could occur in a similar way with or without the climate policy shock. In this context, the effect of the policy shock induces a shift the probability distribution of the small productivity shocks and thus cause an adjustment in the PD of j. We formalise this intuition by introducing the following assumption: the idiosyncratic shocks are independent from the policy shock. It is possible to show that the PD adjustment under the climate policy shock scenario P is equal to:

$$\Delta q_j(P) = q_j(P) - q_j(B) = \int_{\theta_j(B)}^{\theta_j(P)} \phi(\eta_j)\, d\eta_j, \tag{14}$$

with $\theta_j(P) = \theta_j(B) - \xi_j(P)$. Then, assuming that the policy shock on assets is proportional to the shock on GVA via the elasticity $\xi_j = \chi_j \, u_j^{\text{GVA}}(P)$, we obtain the following properties.

In this section we derive analytically the adjustment in the bond default probability (PD) as a function of the climate policy shock. Based on this result, we then derive the adjustment in the bond value and bond spread. The results are formalised in Proposition 2. As it turns out, the adjustment depends on the combination of economic activities (e.g. green versus brown) in which each bond issuer is engaged.

Proposition 1. Given the investor's information set, the adjustment $\Delta q_j(P)$ in default probability of j under Climate Policy Shock Scenario, the following properties hold.

(i) $\Delta q_j(P)$ increases with GVA shock magnitude $|u_j^{\text{GVA}}(P)|$ if $u_j^{\text{GVA}}(P) < 0$, and decreases viceversa (under mild condition on ϕ);

(ii) $\Delta q_j(P)$ is proportional to the GVA shocks on climate relevant sectors (in the limit of small Climate Policy Shock):

$$\Delta q_j(P) \approx -\chi_j \, (u_{j,\text{PrFos}}^{\text{GVA}} \, w_{j,\text{PrFos}}^{\text{GVA}} + u_{j,\text{ElFos}}^{\text{GVA}} \, w_{j,\text{ElFos}}^{\text{GVA}} + u_{j,\text{ElRen}}^{\text{GVA}} \, w_{j,\text{ElRen}}^{\text{GVA}}). \tag{15}$$

The proofs of all the propositions are reported in the Appendix.

Proposition 2. Consider Δv_j^* defined as the change in the discounted expected value of the corporate bond, v_j^*, conditional to a Climate Policy Shock Scenario $B \to P$. The following expression holds:

$$\Delta v_j^* = v_j^*(q_j(P) - v_j^*(q_j(B)) = -e^{-y_f \, T} \, \Delta q_j(P) \text{LGD}_j. \tag{16}$$

Conditional to policy shock scenario $B \to P$, and assuming everything else the same regarding the issuer's balance sheet, then the following properties hold:

(i) $\Delta v_j^*(P)$ is negative and increases with magnitude of policy shock $|\xi_j(P)|$ if $\xi_j(P) < 0$;

(ii) $\Delta v_j^*(P)$ is positive and increases with magnitude of policy shock if $\xi_j(P) > 0$, with the constraint $v_j^* \leq 1$.

Definition 1. The Climate Spread Δs_j is defined as the change in the spread s_j, conditional to the Climate Policy Shock Scenario:

$$\Delta s_j = s_j(q_j(P) - s_j(q_j(B)). \tag{17}$$

Proposition 3. Conditional to the climate policy shock scenario, the climate spread $s_j(P)$:

(i) Increases with magnitude of policy shock $|\xi_j(P)|$ if $\xi_j(P) < 0$;

(ii) Decreases with magnitude of policy shock if $\xi_j(P) > 0$;

(iii) For small GVA shocks $u_j^{\mathrm{GVA}}(P)$ it holds:

$$\Delta s_j \approx -\frac{1}{T}\chi_j \times \tag{18}$$

$$\times\, (u^{\mathrm{GVA}}_{j,\mathrm{PrFos}}\, w^{\mathrm{GVA}}_{j,\mathrm{PrFos}} + u^{\mathrm{GVA}}_{j,\mathrm{ElFos}}\, w^{\mathrm{GVA}}_{j,\mathrm{ElFos}} + u^{\mathrm{GVA}}_{j,\mathrm{ElRen}}\, w^{\mathrm{GVA}}_{j,\mathrm{ElRen}}) \tag{19}$$

3.7. Value-at-Risk and Expected Shortfall of investors: dependence on key parameters

In this section we move to consider a leveraged investor with a portfolio of bonds and we derive how its VaR and ES depend on the key parameters of bond default probability q, bond loss-given-default LGD. We denote an investor i's *portfolio value* z_i and *portfolio rate of return* π_i at T, with W_{ij} amount (numeraire) of j's bond purchased by i as:

$$z_i(T) = \sum_j W_{ij} v_j(T), \qquad \pi_i = \frac{z_i(T) - z_i(t_0)}{z_i(t_0)}. \tag{20}$$

We then introduce the definition of the Climate Value-at-Risk, which captures the notion of the worst case loss, for a given level of confidence. In order to overcome some well known limitations of the Value-at-Risk (e.g. it is not a coeherent risk measure and it is not sensitive to events in the tail of the distribution), the Expected Shortfall (ES) is widely used in finance and regulation. The ES captures the notion of the average worst-case loss, i.e. the loss that can occur, once the threshold of the VaR threshold is reached. The formal definitions are provided below.

Definition 2. The **Climate VaR** is defined as the Value-at-Risk of the portfolio of the investor, conditional to Climate Policy Shock Scenario with π portfolio return, $\psi_P(\pi)$ distribution of returns conditional to the climate policy shock, and c^{VaR} is the confidence level.

The expression reads:

$$\text{ClimateVaR}(P) = \int_{-1}^{\text{ClimateVaR}} \psi_P(\pi)\, d\pi = c^{VaR}. \tag{21}$$

Definition 3. The **Climate Expected Shortfall** is the average of the losses above the ClimateVaR:

$$\text{ES}(P) = \frac{-1}{c^{VaR}} \int_0^{c^{VaR}} \text{ClimateVaR}_\gamma\, d\gamma. \tag{22}$$

.

We now proceed to state some results on the dependence of ES on key parameters. Figure2 shows the distribution of losses of the bond portfolio and its associated ES for selected values of q and ρ. As q and ρ increase the distribution of losses is reshaped so that the ES moves to the right. This means that the expected "worst-case" losses increase both with higher bond default probability and with bond default correlation. This is stated in the following Proposition.

Proposition 4. Conditional to the policy shock scenario $B \to P$, the following properties hold:

(i) ClimateVaR(P) and ES(P) increase with magnitude of policy shock $|\xi_j(P)|$ if $\xi_j(P) < 0$, and decrease viceversa;

(ii) ClimateVaR(P) and ES(P) increase with the default probability adjustment $\Delta q_j(P)$ of bond j.

Figure 3 shows the VaR of the investor's portfolio as a function of q for selected values of the correlation ρ among the bonds in the portfolio. In the absence of correlation, $\rho = 0$, the curve shows a very gradual increase of VaR with q. Notice that scale of the horizontal and vertical axis are the same. Thus, the VaR has a low sensitivity to q (i.e. it increases with q proportionally with sensitivity close to 1). For increasing values of correlation, $\rho > 0$, the VaR shows a concave shape in q. This means that for values of q in the empirically relevant range of $0 \leq q \geq 0.1$ the sensitivity is larger than 1. We find similar results for the ES (figure not shown). We conclude that ES also shows a low sensitivity to q i bond default correlation and moderate sensitivity in presence of correlation.

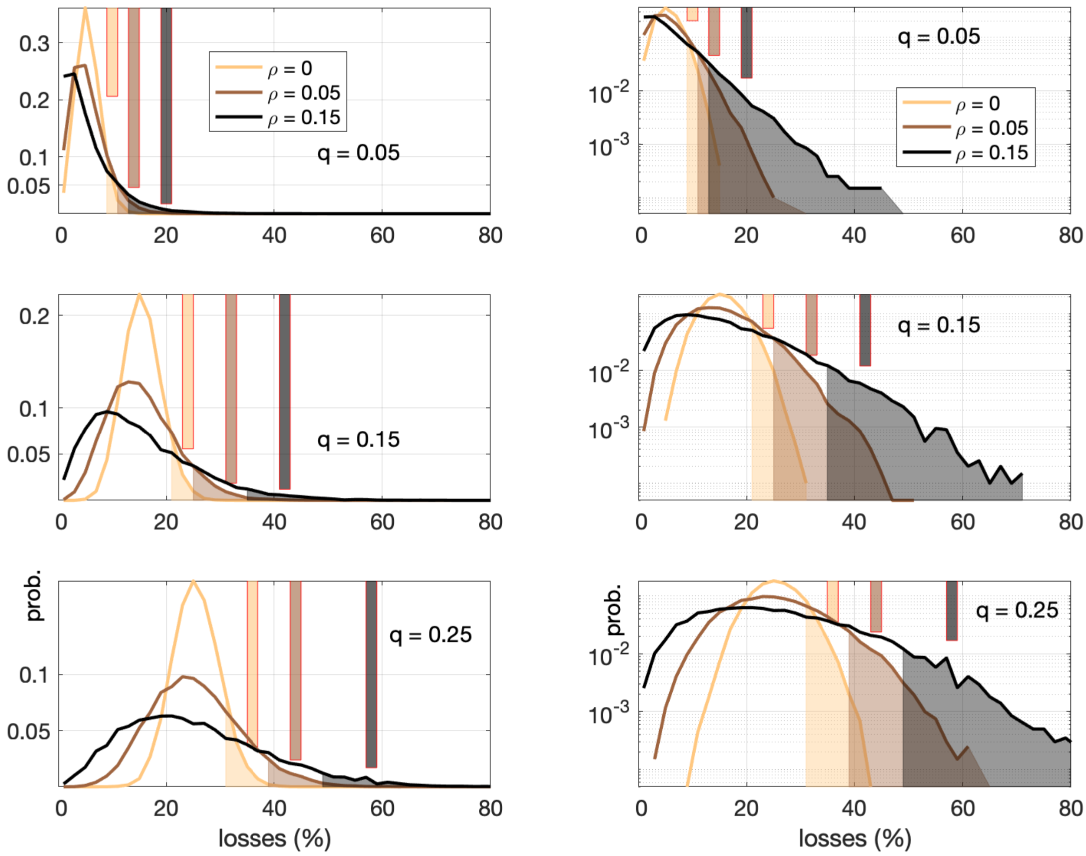

Figure 2: Distribution of probability of losses in percentage in a portfolio of 100 bonds, for varying levels of q and correlation ρ. **Left panels**: distribution of losses in linear scale, for selected values of individual bond probability q, increasing from top to bottom panel. In each panel, three selected level of correlation ρ are shown with color code indicated in the legend. The area plots indicate the right tail of distribution of the losses exceeding the 95% Value-at-Risk. The vertical bars (in color codes corresponding to ρ levels) indicate the position on the x-axis of the value of the Expected Shortfall of the distribution of losses. **Right panels**: same as left panels but in log scale in order to show the details of the tail of the distribution of losses.

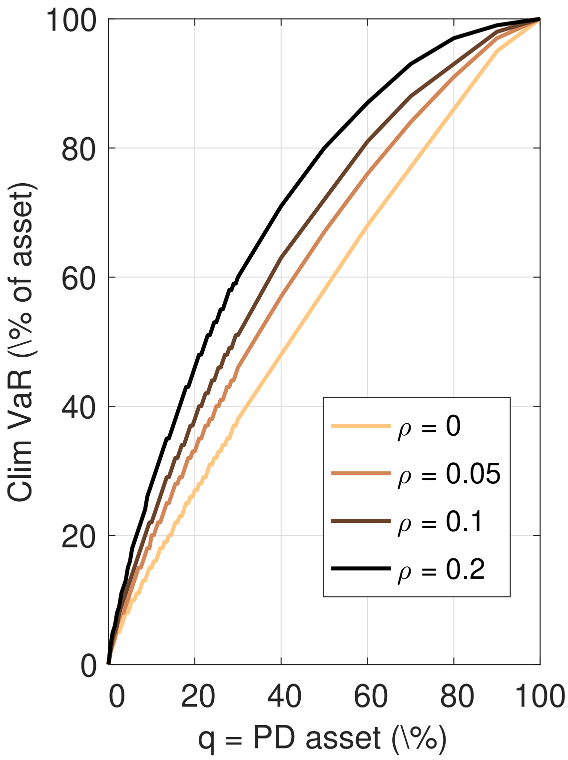

Figure 3: VaR as a function of q for varying ρ

3.8. Probability of default of a leveraged investor and its dependence on key parameters

In this section, we consider a financial investor financed with leverage, i.e. with leverage level > 1, with leverage defined as the ratio of total asset over equity. We consider a portfolio of zero-coupon corporate bonds, with the same default probability q, and the same loss-given-default LGD =1. The portfolio is equally weighted across the bonds.

In Figure 4 we investigate how the investor's PD depends on bond default probability q and correlation ρ.

Proposition 5. The following properties hold:

(i) The investor's PD increases with the bond default probability q;

(ii) The investor's PD increases (decreases) with the bond correlation ρ, for low (high) enough levels of bond default probability q.

The results highlight the importance of considering the uncertainty on the scenarios, even if they are modelled as exogenous. Indeed, small change in bond PD imply large changes in the investor's PD. Hence, financial stability is highly sensitive to climate policy shock scenarios.

3.9. Sensitivity of expected shortfall and PD to the probability of occurrence of scenarios

If the investor has full knowledge of the key parameters of the model, including the probability p_l of occurrence of the various possible scenarios, she can compute exactly VaR, ES and PD. However, in reality the probability of occurrence of the various possible scenarios is difficult to estimate.

Therefore, in this section, we investigate the role of the probability of occurrence of different scenarios. For the sake of simplicity, we consider the case of two scenarios (Mild, Adverse) that are mutually exclusive, i.e. $p_M = 1 - p_A$. In the Mild Scenario, bond default probability and correlation are low: $(q = 0.01, \rho = 0.01)$. In the Adverse scenario, the bond default probability varies in [01] and and the correlation is higher $\rho = 0.3$.

Figure 5 shows the dependence of ES and PD of the investor on the bond probability of default q, for varying levels of probability of occurrence of the adverse scenario.

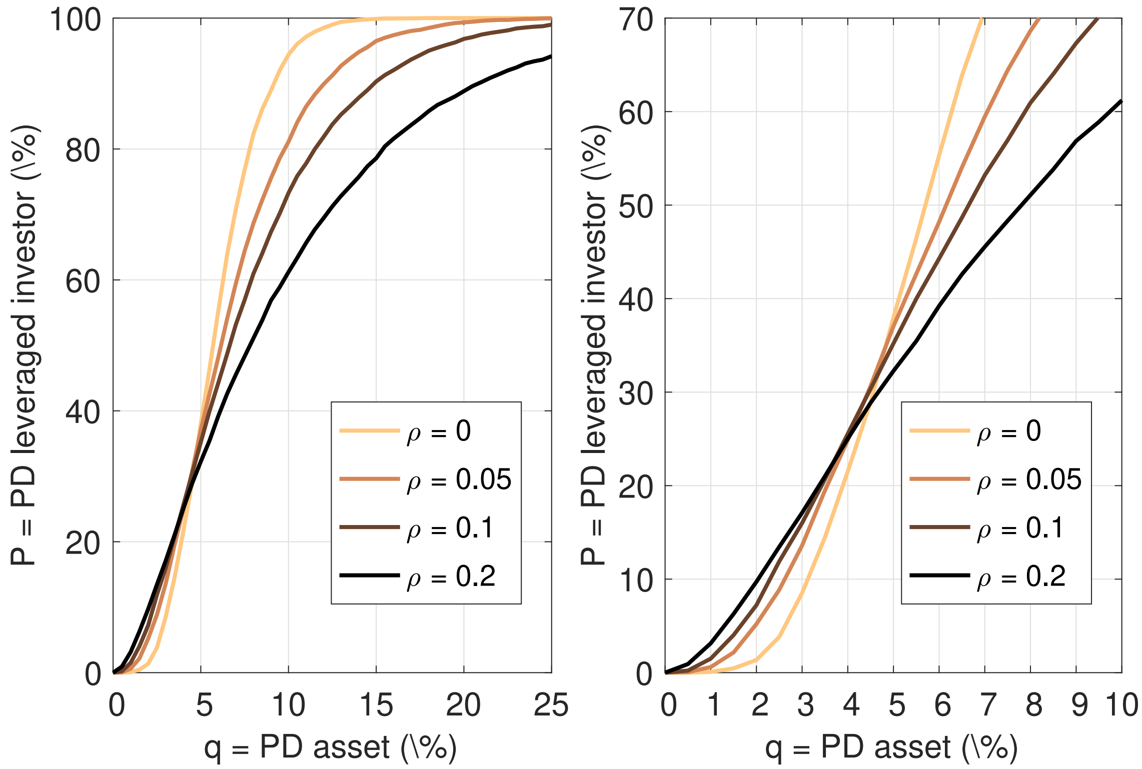

Figure 4: PD of the investor versus bond probability of default q, for varying levels of correlation ρ.

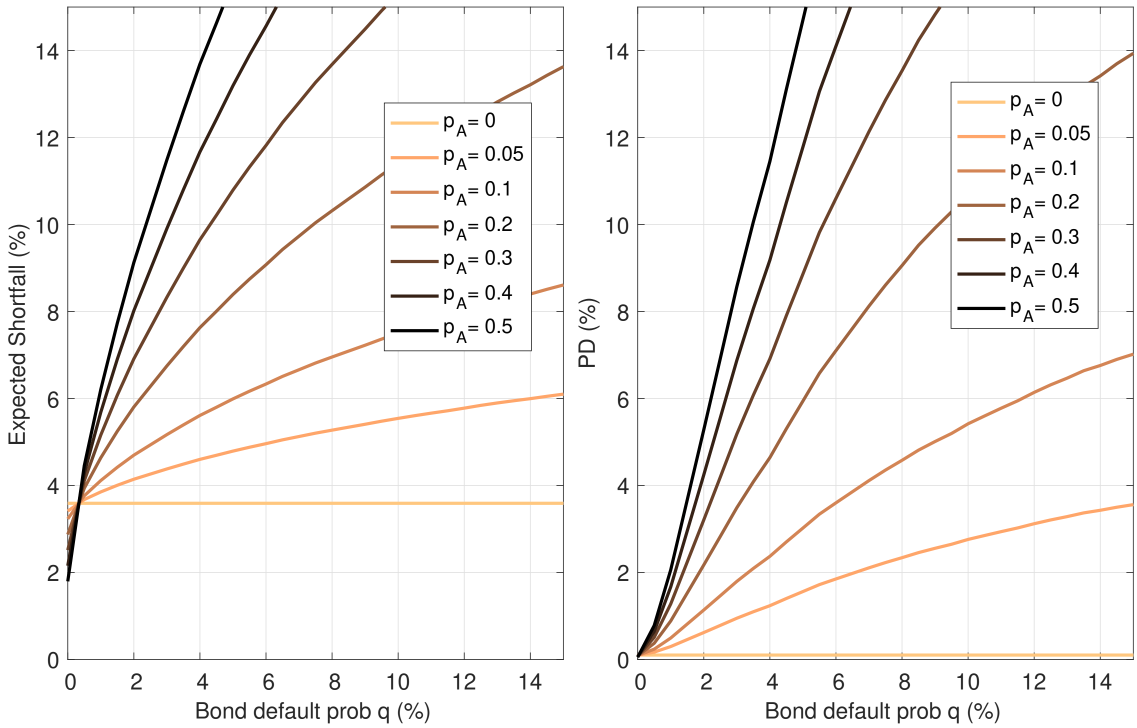

Figure 5: ES and PD of the investor versus bond probability of default q, for varying levels of probability of occurrence of the adverse scenario

For example, consider the following two points in the right panel: point 1: $q = 2, p_A = 0.05$ which correspond to $PD = 1\%$, and point 2: $q = 5, p_A = 0.4$, which corresponds to $PD = 10\%$. The level of uncertainty concerning the severity of the scenario and its occurrence implies a possible mistake of a factor 10 in the estimation of the PD.

3.10. Endogenous probability of occurrence of scenarios

We now analyse a more complex but realistic situation in which the p_l are endogenous. We model in the simplest way the fact that perception of low probability of adverse scenario can be self-defeating and lead to financial instability. To this end, $p_l = f(p_l)$. Let's consider two scenarios mild and adverse occurring with probability p_M and p_A. In the mild scenario $q = 1\%$ and in the adverse scenario $q = 5\%$. If the probability of occurrence of the two scenarios is exogenous and given for instance by $p_M = 0.9$ and $p_A = 0.1$, there is a certain level of PD for the investor. If however, p_M and p_A are endogenous, i.e. low perception of risk leads to insufficient investments and eventually to higher risk, it could be that the actual probability are e.g. $p_M = 0.1$ and $p_A = 0.9$. This means that the PD is dominated by the event of $q = 5\%$. This implies that investors face a PD much higher than expected. Financial supervisors are also caught off-guard. Financial instability ensues. It follows that the underestimation of p_l and the choice of the set of scenarios is key for financial stability.

4. Empirical application

In this section, we apply the model to the sovereign bonds' portfolio of OeNB. We focus on sovereign bonds for three reasons. First, sovereign bonds represent the largest share of central banks' portfolio. 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 during the COVID-19 emergency, 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. We consider, under a climate policy scenarios, the impact of the country's debt/GDP ratio, expected economic growth, and also the country's dependence on fossil fuel energy and electricity, on the value of the 10-years sovereign bonds' spread and the 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 disordered transition to a mild or tight climate policy scenario 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.

Country code	Country	Region in models	WITCH: bond shocks (%)	WITCH: yield shock (%)	GCAM: bond shock (%)	GCAM : yield shock (%)
AT	Austria	EUROPE	1.30	-0.16	0.13	-0.02
AU	Australia	REST_WORLD	-17.36	2.45	n.a.	n.a.
BE	Belgium	EUROPE	0.84	-0.10	0.03	0.00
CA	Canada	PAC_OECD	-5.21	0.67	-18.29	2.61
CH	Switzerland	REST_WORLD	3.65	-0.44	n.a.	n.a.
CL	Chile	LATIN_AM	-6.10	0.79	-4.22	0.54
CR	Costa Rica	LATIN_AM	-0.50	0.06	-0.34	0.04
CZ	Czech Republi	EUROPE	1.24	-0.15	-0.11	0.01
DE	Germany	EUROPE	-1.27	0.16	1.18	-0.15
DK	Denmark	EUROPE	-0.36	0.04	-0.42	0.05
EE	Estonia	EUROPE	3.75	-0.45	0.51	-0.06
ES	Spain	EUROPE	1.58	-0.19	1.05	-0.13
FI	Finland	EUROPE	2.64	-0.32	0.47	-0.06
FR	France	EUROPE	1.34	-0.16	0.21	-0.03
GB	United Kingdo	EUROPE	-0.46	0.06	0.66	-0.08
GR	Greece	EUROPE	0.50	-0.06	-0.07	0.01
HU	Hungary	EUROPE	0.78	-0.10	-0.08	0.01
IE	Ireland	EUROPE	1.94	-0.24	0.42	-0.05
IT	Italy	EUROPE	-1.42	0.18	0.33	-0.04
JP	Japan	PAC_OECD	-5.05	0.65	-5.48	0.71
KR	Korea	REST_ASIA	-0.48	0.06	-0.50	0.06
LT	Lithuania	EUROPE	2.60	-0.32	0.58	-0.07
LU	Luxembourg	EUROPE	1.85	-0.23	0.44	-0.05
LV	Latvia	EUROPE	2.45	-0.30	0.47	-0.06
MX	Mexico	LATIN_AM	-6.30	0.82	-2.71	0.34
NL	Netherlands	EUROPE	-5.05	0.65	-0.91	0.11
NO	Norway	REST_WORLD	-14.82	2.05	n.a.	n.a.
PL	Poland	EUROPE	-12.85	1.75	-2.49	0.32
PT	Portugal	EUROPE	1.86	-0.23	0.27	-0.03
SE	Sweden	REST_WORLD	-1.54	0.19	n.a.	n.a.
SI	Slovenia	EUROPE	2.30	-0.28	0.32	-0.04
SK	Slovak Republ	EUROPE	-0.36	0.05	-0.77	0.10
TR	Turkey	REF_ECON	-2.63	0.33	-0.01	0.00
US	United States	NORTH_AM	-4.04	0.52	-1.06	0.13

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.

The largest negative shocks on individual sovereign bonds' value are associated to Australia (Rest-World, -17,36%), Norway (Rest-World, -14,82%) and Poland (Europe, -12,85%) that indeed show the highest yields (i.e. the climate spread). These shocks are led by the large contribution (direct or indirect, such as the wealth fund in the case of Norway) to GVA and thus on country's GDP of fossil fuel-based primary and secondary energy sources, and by the WITCH IAM's trajectories of these specific sectors, under a tighter climate policy scenario (StrPol-450). In contrast, we notice positive shocks for sovereign bonds of countries located in Austria (Europe, 1,30%) and several Southern European countries (e.g. Portugal, 1,86%). 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 IAM's trajectories of these specific sectors. 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.

Model	Scenario	Region	Asset Shock (%)
WITCH	LIMITS-RefPol-450	REST_WORLD	-0,367
WITCH	LIMITS-RefPol-450	REST_WORLD	-0,350
WITCH	LIMITS-RefPol-450	PAC_OECD	-0,329
WITCH	LIMITS-RefPol-450	NORTH_AM	-0,110
WITCH	LIMITS-RefPol-450	EUROPE	-0,078
WITCH	LIMITS-RefPol-450	EUROPE	0,005
WITCH	LIMITS-RefPol-450	EUROPE	0,016
WITCH	LIMITS-RefPol-450	EUROPE	0,018
WITCH	LIMITS-RefPol-450	EUROPE	0,021
WITCH	LIMITS-RefPol-450	EUROPE	0,083
WITCH	LIMITS-StrPol-500	REST_WORLD	-0,127
WITCH	LIMITS-StrPol-500	PAC_OECD	-0,082
WITCH	LIMITS-StrPol-500	EUROPE	-0,024
WITCH	LIMITS-StrPol-500	EUROPE	-0,019
WITCH	LIMITS-StrPol-500	LATIN_AM	-0,015
WITCH	LIMITS-StrPol-500	EUROPE	0,010
WITCH	LIMITS-StrPol-500	EUROPE	0,011
WITCH	LIMITS-StrPol-500	EUROPE	0,013
WITCH	LIMITS-StrPol-500	REST_WORLD	0,040
WITCH	LIMITS-StrPol-500	EUROPE	0,118

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. Europe is composed of different countries that we cannot disclose for confidentiality reasons.

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% negative shock (%) on the value of a single OECD sovereign bonds (Australia) weighted for the role of the country issuing it on OeNB's portfolio. In contrast, the most positive shock +0,118%, results from the exposure to a single sovereign bond's issuer located in Europe (Austria). 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.

The total negative shock on OeNB's portfolio is equal to 1,234%, while the total positive shock equals 0.143%. These shocks could look small but in assessing their impact on the financial stability of a financial institution we should consider its leverage and financial risk conditions. It is true that central banks (in particular in countries that have monetary sovereignty) cannot fail. Nevertheless, sovereign bonds issued by OECD countries (and in particular by those who are affected by the largest shocks) can be easily found in the portfolios of commercial banks, which declare an average (post financial crisis) leverage equal or higher than 30. With such a leverage, a shock of 1.3% would lead to at least 30% capital losses, and thus be relevant for the financial stability of the bank.

5. Conclusion

In this preliminary work in progress version of the manuscript, we develop a model to price forward-looking climate risk in corporate and sovereign bond value and portfolios. We demonstrate that uncertainty on the type and occurrence of feasible climate transition scenarios leads to a massive underestimation of the PD of the investor's bond portfolio (10 times). Indeed, while the Climate VaR and ES show low sensitivity to small changes in bond PD q, small changes in q imply large changes in PD of a leveraged investor. In addition, the effect on the investor's PD is amplified if the probability of occurrence of the feasible climate transition scenarios is endogenous.

We provide then an empirical application to the sovereign bonds' (non-monetary policy) portfolio of the Austrian National Bank. We find that countries where low-carbon sectors play a large role in the economy have lower bond yields relative to countries where fossil fuels still play a large role. In particular, in carbon intensive countries, the cost of climate misalignment is reflected in a higher Climate Spread and affects sovereign risk and portfolio's performance. Climate Stress-testing exercise should allow for a wide enough set of scenarios to avoid massive underestimation of losses. The results imply that identification of scenarios is critical and subject to moral hazard. Further, the Climate VaR and ES is a first step to integrate climate risk in familiar risk metrics, however it has important limitations. Finally, the empirical application shows that countries where Climate Policy Relevant Sectors (i.e. sectors that directly or indirectly rely on fossil fuels for their business) represent a large share of the economy, can face a large and abrupt decrease in the value of the sovereign bonds and an increase in the Climate Spread in a 2 °C aligned climate transition scenario.

The results have important implications for the selection of relevant climate transition scenarios in climate stress-testing exercises, and for the assessment of climate-related financial risk for supervisory and prudential policy purposes.

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