[Version February 11, 2020]

The Climate Spread of sovereign bonds

Stefano Battiston[a], Irene Monasterolo[b,1]

[a] *University of Zurich and FINEXUS Center*
[b] *Vienna University of Economics and Business, Austria*

Abstract

A disorderly low-carbon transition could bring new sources of risk for financial stability for countries that are lagging behind in decarbonizing their economy. In this paper, we quantitatively assess the impact of forward-looking climate transition scenarios aligned with the Paris Agreement's climate targets, on government bond yields and spreads, after controlling for conventional country-specific and global determinants of sovereign risk. We use non-monetary policy portfolio data on OECD countries' sovereign bonds that compose the Austrian National Bank's portfolio. Then, we analyse the impact on the performance of the portfolio of a central bank with a traditional (market mimicking) exposure and a *green* strategy. As a main innovation on traditional financial pricing models, our approach allows to embed the deep uncertainty, non-linearity and endogeneity of climate risk in the performance of financial contracts and investors' portfolios. We find that countries where low-carbon sectors play a large role in the economy have lower bond yields and spreads relative to countries where fossil fuels still play a large (direct or indirect) role. In carbon intensive countries, the cost of climate misalignment could be reflected in a higher *Climate Spread* and affect sovereign risk and investors' portfolio performance, with potential implications on financial stability.

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

[⋆] This is a first version of a work in progress. The authors are very grateful to the Oesterreichische

1. Introduction

Achieving the climate targets of the Paris Agreement (i.e. limiting global temperature increase above pre-industrial levels to 2) requires a deep decarbonization of countries' economies and a transition to low-carbon energy technologies (IPCC 2018). Nevertheless, fossil fuels and carbon-intensive activities still represent a large share of countries' Gross Value Added (GVA) (e.g. Norway), and increasing even after the announcement of the Paris Agreement (e.g. Australia, OECD data). To signal the market towards an orderly transition, the timely and coordinated introduction of climate policies (e.g. a carbon tax, carbon pricing, Stiglitz and Stern 2017, IMF 2019) has been advocated. However, governments are delaying climate policies' implementation. This means that we could be moving towards a scenario characterised by a *disorderly* low-carbon transition, i.e. a situation in which the introduction or the impact of late climate policies is not fully anticipated by market players (see the reference to climate transition risk in Battiston et al. 2017, NGSF 2019). It has been increasingly recognized that a disorderly transition would lead to asset prices volatility if large and correlated asset classes are involved (Monasterolo et al. 2017) with implications on financial stability (Gros et al. 2016, Battiston et al. 2017). In this context, firms whose revenues derive directly or indirectly from carbon-intensive activities could face significant losses if they are not able to timely adapt to the new policy scenario. These losses could be translated in the value of their financial contracts (e.g. equity holdings, bonds, loans) and in the contribution to the economy's Gross Value Added (GVA). Shrinking sectors' performance would negatively affect sovereign fiscal position (via lower fiscal revenues) and economy (GDP), and the financial position, via changes in the value of

---

Nationalbank - Central Bank of Austria (OeNB) for the support in the collection of the OeNB's portfolio data. In particular, we would like to thank Pirmin Fessler, Florian Glantschnig, Andreas Breitenfellner and Wolfgang Pointner for the collaboration on data collection at OeNB, and Alan Roncoroni (UZH) for the useful comments on previous versions of the manuscript. IM wants to thank Tom Heller, Gireesh Shrimali, and John Weyant at Stanford University and for fruitful discussions on the paper during IM's visiting research in Stanford in spring/summer 2019. We thank the participants of the European Commission Sustainable Finance Conference in January 2019, of the Sustainable Finance workshop organized by the European Commission Joint Research Center in Ispra in July 2019; of the Econometric models of climate change conference (EMCC IV) in August 2019; of the CREDIT conference in Venice in September 2019; of the Network for Greening the Financial System's Green central banking conference 2019 for the useful comments.

sovereign bonds (considering the change in investors' expectations and reactions to change in market fundamentals). As such, climate transition risk could materialize in the portfolios of investors exposed to the sovereign bonds of the affected countries. Recently, several central banks involved in the Central Banks and Financial Regulators' Network for Greening the Financial System (NGSF) developed the notion of *climate Minsky Moment*, i.e. a sudden drop in the value of carbon assets prices (Carney et al. 2019) while the Bank for International Settlements (BIS) talked about a *Green Swan*, i.e. a scenario of global financial distress triggered by climate change (Bolton et al. 2020). The NGSF, along with the International Monetary Fund is advocating the introduction of climate financial pricing models and Climate Stress-testing exercise to disclose investors' exposure to forward looking climate transition risk. More recently, several financial inst

However, pricing forward-looking climate risks in financial contracts and portfolios' performance is challenging due to the nature of climate risks. The literature has emphasized the importance of the characteristics of climate change, i.e. deep uncertainty and tail events (Weitzman 2009, 2011), tipping points (Solomon et al. 2009, Lenton et al. 2019) and non-linearity (Ackerman 2017) leading to potential domino effects (Steffen et al. 2018). Moreover,the endogeneity between climate policies and investors' expectations on financial risk deriving from the same policies generates the possibility of multiple equilibria (Battiston and Monasterolo 2018).

Thus, standard financial risk pricing models (Merton 1974, Black and Cox 1976) are not adequate to deal with the complexity of climate and of financial risks (Battiston et al. 2016a) because they build on average value and most likely scenario, on assumptions of linearity and normal distributions, and on backward-looking benchmarks that are at odd with the characteristics of climate risk.

The classical literature on climate economics has the merit to have brought the conversation on climate mitigation at the centre stage of the economic profession (Nordhaus 2019), opening a debate on costs and opportunities for action. The last generation of Integrated Assessment Models (IAMs) provides the economic trajectories conditioned to climate scenarios but do not include finance and its complexity and thus cannot support a financial risk assessment of climate scenarios (Battiston and Monasterolo 2018).

In this paper, we develop a novel methodological framework, CLIMAFIN, that bridges the gap between climate economic modelling and financial risk pricing in sovereign bonds. Our approach allows to embed forward-looking climate transition risk scenarios provided by climate economic models reviewed by the IPCC report into traditional financial pricing models used by academics and financial supervisors, to provide a quantitative assessment of climate risks in sovereign bonds and investors' portfolios. We consider the forward-looking climate transition scenarios aligned with the Paris Agreement's climate targets (2°C) and related economic and energy technologies trajectories provided by two IAM (GCAM and WITCH). We translate the impact of the shocks on the value, yields and spreads of the OECD countries' sovereign bonds included in the Austrian National Bank (OeNB)'s non monetary policy portfolio, after controlling for conventional country-specific and global determinants of sovereign risk. Finally, we analyse the impact on the performance of the portfolio of a central bank with a traditional (market mimicking) exposure and a *green* strategy. As a main innovation on traditional financial pricing models, our approach allows to embed the forward-looking dimension, deep uncertainty, non-linearity and endogeneity of climate risk in the performance of financial contracts and investors' portfolios. We find that countries whose economies are (mis)aligned are more exposed to climate transition risk and this could be reflected in the value of their sovereign bonds and in their Climate Spread.

The paper is organized as follows. Section 2 discusses the characteristics of climate transition risk and scenarios, and the challenges to embed them in traditional financial pricing models. Section 3 presents the IAMs' climate policy scenarios and trajectories for economic and energy sectors. Section 4 presents the new climate financial pricing model. Section 5 provides an application to the climate risk pricing of OECD sovereign bonds and OeNB's portfolio. Section 6 concludes with implications for financial supervision.

2. Review of the State of the Art

In this section, we briefly recall the literature on sovereign bonds' valuation and on climate risk assessment, and we identify the main challenges for pricing climate risks in financial contracts and investors' portfolios.

2.1. Sovereign risk valuation

While a large body of literature on non-defaultable sovereign exist, the geopolitical and economic events of the end of the 20th century (such as the fall of the Berlin wall and the disgregation of the former URSS, the 2008 financial crisis and the sovereign debt crisis) led several scholars to focus on defaultable sovereign bonds (Duffie and Singleton 1999, Duffie et al. 2003, Gray et al. 2007). More recently, in the aftermath of the Great Financial Crisis, the worsening of macroeconomic fundamentals and the increase in governments' debt, relative to GDP[1] lead economists to pay growing attention to default conditions also in high-income countries, focusing on the role of economic fundamentals and of governance. However the evidence is not conclusive on what are the dominant conditions for sovereign default. Despite it is generally considered very difficult to force independent sovereigns to repay outstanding debts (especially if governments can issue their currency), several empirical studies considers that sovereigns might be interested in repaying debts. The reason is related to political and economic costs, such as:

- Being (either partially or temporarily) excluded from the capital market (Kletzer and Wright 2000) and reputation (Eaton 1996).
- Losing consent or being voted out of office (Broner et al. 2006).
- Potential domestic unrest (Borensztein and Panizza 2009) and overall the domestic costs of default (Panizza et al. 2009).
- Correction of investors' expectations about country's growth, capital outflows, financial instability, (see e.g. Sandleris, 2008).

On the other hand, scholars focused on the drivers of sovereign bonds' yield spreads, highlighting the challenges of assessing major sovereign credit events (Duffy et al. 2003).

---

[1] See for instance ECB 2011 report `https://www.ecb.europa.eu/press/key/date/2011/html/sp111104_1.en.html`

The main determinants of sovereign credit risk identified by the literature include several factors, such as macroeconomic fundamentals (Arellano 2008), liquidity (Favero et al. 2010), market-related factors (Oliveira et al. 2012) composition of government budget, (Van Landschoot 2004), debt-to-GDP, inflation and taxation (Lemmen and Goodhart 1999), fiscal fundamentals and government announcements of bank rescue packages (Attinasi et al. 2009). However, while none of them seem to be dominant across time and countries, scholars also disagree on the drivers.

2.2. Climate change and financial risk

A recent stream of literature has focused on the analysis of financial actors and markets' pricing of climate risks, in particular those associated to climate policy announcements.

Morana and Sbrana (2019) consider the case of catastrophe bonds contracts (CAT) and find that their multiples, i.e. their return per unity of risk, have not incorporated climate-related risks occurred in the last decade. Indeed, CAT bonds' multiples have experienced a steady decline from a value of 8 in the early 2000s to a record low of 2 from 2015 on, while in the same period, climate-led natural disasters and related losses have increased steadily.

The most of the analyses focused on debt securities, and in particular on bonds. It emerged that green and traditional bonds' prices are not reflecting the information available to investors (Ehlers and Packer 2017). Zerbib (2019) finds that from 2013 to 2017 the yield of a green bond is slightly lower than that of a conventional synthetic bond (i.e. a small premium), while Karpf and Mandel (2018) find, for the US municipal bonds' market, that the returns on conventional bonds are on average higher than for green bonds. These differences can largely be explained by their fundamental properties and not by the "green" label. In the case of loans, de Greiff et al. (2018) find that before 2015 commercial banks did not price climate policy risk in the loans terms for carbon-intensive companies but their behaviour started to change after the Paris Agreement (PA), despite not at significant levels.

In the case of equity contracts, Monasterolo and de Angelis (2020) detect a change on market beta for low-carbon and carbon-intensive indices on the EU and US stock market after the PA, i.e., the systematic risk associated to the low-carbon assets and indices has decreased while the level of systematic risk associated to carbon intensive assets and indices has not increased. In addition, they find that weights of portfolios highly exposed to low-carbon indices increased after the PA. Ramelli et al. (2019) find that investors reacted to two main policy “shocks” in 2016, i.e. Trump’s presidential election and the nomination of Scott Pruitt to head the Environmental Protection Agency (EPA), by rewarding companies in high-emissions industries, at least in the short run. In contrast, Sterner and Mukanjari (2018) did not find unique evidence of equity portfolios’ response the announcement of the US withdrawing from the Paris Agreement. Finally, Alessi et al. (2019) find evidence of a negative Greenium, i.e. the risk premium for the green factor, using a set of European individual stocks and the 25 European Fama-French portfolios.

The role of climate change as a source of risk for sovereign bonds’ valuation has just started to be addressed by the literature. Kling et al. (2018), who focus on the most climate vulnerable low-income countries (V20) exposed to climate physical risk. In a few cases the authors find a slightly higher cost of debt. But caveats applies, such as the peculiarity of sovereign bonds’ markets in low-income countries and the nature of risks (e.g. geopolitical) to consider in the sovereign valuation. In addition, the European Insurance and Occupational Pension Funds (EIOPA) developed a climate risk assessment of the sovereign bonds’ portfolios of European insurance firms, finding that countries where the level of decarbonization of the economy is low (e.g. Poland) would be exposed to higher climate-related financial risk. This, in turn, could be translated via shocks on sovereign bonds’ value to insurance firms’ portfolios in Europe (Battiston et al. 2019).

Despite focusing on different types of financial contracts and climate risks (mostly policy announcements), the literature has addressed climate-related shocks that have already occurred in the past, and that could have represented a structural break in the series of prices and performance. However, an assessment of financial risk, and in particular of sovereign risk, in the context of forward looking climate scenarios has not been carried out yet.

2.3. Challenges for pricing climate risks in financial contracts

Pricing forward-looking climate transition risks, and in particular climate transition risks, along different yet feasible policy and economic trajectories is important to assess the conditions for losses on economic competitiveness and countries' financial stability. This information would inform investors' portfolios' risk management strategies, and financial supervisors and institutions' systemic risk monitoring and risk mitigation strategies (e.g. prudential measures). Nevertheless, it is challenging for several reasons that are linked to the nature of climate risks, which we briefly discuss here (for a comprehensive review, see Monasterolo 2020):

- Non-linearity of impacts. 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 that characterize impacts and their costs. 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).

- Forward-looking nature of risk. 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.

- 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).

Traditional financial risk valuation builds on the identification of the most likely scenarios, and in the computation of the expected values and the estimation of financial risk metrics (e.g. volatility) that are backward looking in nature because they rely on historical values of market prices (Battiston 2019). Those models are also based on constrained by strong assumptions on equilibrium conditions, normal distribution of shocks, linearity of impacts, complete markets and lack of arbitrage. As such, they are inadequate to deal with the characteristics of climate risks.

In this analysis, we focus on climate transition risk because, as highlighted by the NGSF (2019) while climate physical risk would be more visible in the mid to long term, climate transition risk would be more financially relevant in the short term. Overall, the notion of climate transition risks stands on the concept of disorderly low-carbon transition (Battiston et al. 2017; NGSF 2019). The transition to a low-carbon economy could occur in an orderly or in a disorderly way. Orderly means that the climate policies for decarbonizing the economy and achieving the climate targets are introduced early and in a coordinated way among countries. In this context, investors are able to anticipate the climate policy introduction by pricing it in their risk management strategies and thus revising their investment allocations (ideally by decreasing their exposures to carbon-intensive activities and increasing their exposures to low-carbon activities). In this context, carbon-intensive (low-carbon) firms can adjust their business strategy, avoiding large shocks in their market share, and thus on the value of the financial contracts associated to them (e.g. equity holdings, corporate bonds). Disorderly refers both to the way policies are implemented and to the way the market responds to the policies. If climate policies are introduced in a late and sudden way with regard to the decarbonization targets (e.g. EU2030 climate and energy targets), they could trigger a disorderly response from financial actors 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 in their market share, thus affecting the value of the financial contracts issued by such firms.

The lack of investors' anticipation of climate physical and transition shocks could have long-lasting consequences for the economic and financial conditions of a country. 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 (Mercure et al. 2018). 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, see e.g. the spread on Italy' sovereign bonds (Battiston 2019).

3. Climate-financial decision theory under deep uncertainty

Pricing climate in the evaluation of financial contracts and portfolio's management strategies requires considering a set of conditions that pertain *the nature of climate risks*. 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 2013, 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). Thus, they overlook 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 Value at Risk (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).

Under these conditions, traditional financial pricing models (Merton 1974, Black and Scholes 1973, Black and Cox 1976, among the most relevant examples of ex-ante evaluation of financial contracts) are less relevant. Indeed, they rely on assumptions of normal probability distribution of shocks, deterministic default conditions, single pricing that is informed by historical portfolio or asset's performance, deterministic volatility, and perfect hedging.

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.

In this paper, we contribute to this stream of research by developing a climate-financial decision theory under uncertainty. Our approach combines climate economics modelling, financial risk analysis rooted on network theory, and financial risk pricing under deep uncertainty. Our approach is modular and is organized in the following steps:

- We select policy relevant 2°C aligned climate mitigation scenarios that correspond to a certain level of Greenhouse gases (GHG) emissions' concentration in the atmosphere (ref. IPCC 2014);
- We calculate economic trajectories associated to a disorderly transition (P) from the Business as Usual (BAU, i.e. no climate policy) to a mild or tight climate mitigation scenario, for fossil fuels and renewable energy sectors and sub-sectors;
- We assess the impact of the shock on firms and sectors' profitability and we compute the change in market share and Gross Value Added (GVA) for sectors and firms in fossil fuels and renewable energy sectors;
- We model the climate shock transmission to government's fiscal revenues, to the change in the value of the sovereign bond and its risk associated, by introducing the *climate spread*;
- We apply the model to historical sovereign bonds data (10 years maturity) for OECD countries;
- We calculate the Climate VaR and compute the largest gains/losses on the OeNB's portfolio.

The analytical description and empirical analysis are discussed in the following section.

4. Methodology

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

4.1. Investors' information set and risk management strategy

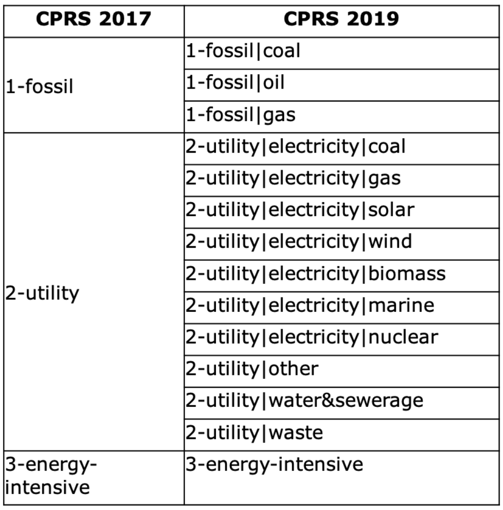
We consider a risk averse investor that aims to assess the climate risk of her portfolio of sovereign bonds in a context of incomplete information and deep uncertainty (Keynes 1973, Knight 1921, Greenwald and Stiglitz 1986, Nalebuff and Stiglitz 1983). In this context, future asset prices are subject to shocks that depend on the sovereign future economic performance, the risk premia demanded by the market, as well as the climate policy introduction and the outcome of the energy transition of individual countries.

The information set of the investor and of the market includes two components: sovereign climate transition shocks (for both fossil fuel based and renewable energy based sectors) and sovereign idiosynchratic shocks. The investor sets her risk management strategy based on the computation of the Value at Risk (VaR). The investor considers different feasible climate policy scenarios (but has no information on the probability associated) for which she can calculate the impacts (negative or positive) on the market share of fossil fuels or renewable energy-based sectors and firms. The investor's risk management objective is to keep her VaR at a certain target level. The investor is subject to incomplete information on her (and competitors') exposure to risk stemming from a disordered transition from a climate policy scenario to another one, uncertainty on the outcome of the country's energy transition, and no information on the probability distribution. Thus, her risk management strategy is to consider a set of feasible climate transition scenarios that her portfolio should withstand, and then compute the VaR conditional to those scenarios.

4.2. 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), which was originally introduced in Battiston et al. (2017). NACE codes (4 digits) are mapped to CPRS (2017), which identifies the main sectors that are relevant for climate transition risk (fossil-fuel, electricity, energy-intensive, transportation, buildings). CPRS classification departs from the NACE classification of economic sectors (at 4 digit level) in so far, it catches the energy and electricity technology of the economic activity. Its refinement (i.e. CPRS Rev2 2019) provides a more granular classification of the economic activities in terms of technologies (utility—electricity—wind, solar, gas).

Within S, we focus on the fossil fuel and renewable energy primary and secondary sectors and subsectors, 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).



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 to be mapped into the IAMs' variables and NACE 4 digit sectors

4.3. Sovereign climate transition shocks

In the model, the investor knows that the sovereign entities issuing bonds have committed to achieve certain climate targets, i.e. investments in renewable energy and energy efficiency (e.g. the EU2030 targets), as stated in their NDCs. Thus, the climate and energy targets of each countries are assumed to be known by the investor. These targets translate in a share of energy and electricity produced by renewable energy sources.

However, for each country, the investor does not known if and when the country will introduce climate policies to foster the alignment of the economy to its targets. She also does not know along which economic trajectory, which means, the change in energy mix of the economy that leads to a change in the market share of different renewable/fossil sub-sectors of the economy and thus the revenues of the firms in those sectors.

The investor does not have priors on the probability of these events and assumes that if a country implements the low-carbon transition, then it does so by switching from its BAU scenario to one of the climate policy scenarios described by the scientific community (i.e. the energy and economic scenarios based on IEA roadmap and IPCC climate scenarios, see Kriegler et al. 2013, IPCC 2014). This assumption is motivated by the fact that there is policy and scientific consensus on these climate policy scenarios and their trajectories.

The transition of a country from BAU to a climate policy scenario can occur orderly or disorderly. Orderly, means here that the introduction of a climate policy is carried out timely enough for the country to achieve its renewable energy targets and with a public and predictable schedule. In this scenario, investors can anticipate it and discount the effects on asset prices of the economic activities affected. For instance, the phasing out of coal-based electricity plants is announced to happen with a certain schedule, which is maintained and the market players know that it will be maintained. Thus, they can discount the future value of investments in assets that have these plants as underlying, accordingly, and they can price the risk associated to their exposure to financial contracts related to those plants.

In contrast, disorderly means that the transition is carried out at a schedule that is not predictable by markets and investors, e.g. the government introduces the climate policy in a late and sudden way, or retroactively revise its policies. In this case, we assume that the climate policy shock stemming from a disordered transition is not anticipated (despite potentially expected) by the investor. This is due to the backward looking nature of the benchmark considered by asset managers and on which asset managers' performance (and thus remuneration) is assessed (Silver 2017). It is common knowledge that asset managers take investment decisions based on the benchmark in their respective markets (Greenwald and Stiglitz 1983). Recent research shows that the market benchmark is carbon intensive (see e.g. Battiston and Monasterolo 2019 for the case of corporate bonds market benchmark against which the European Central Bank's corporate bonds purchase (CSPP) has been assessed).

If the investor cannot anticipate the policy shock, then we can assume that she cannot discount correctly the effect of a climate policy on the change in asset prices of the economic activities affected by the transition. A failure to anticipate the climate policy shock leads to a failure in pricing it correctly. In turn, this has potentially severe implications on price volatility, on portfolio's performance and financial stability.

It is important to notice that the assessment of the policy shock could be incorrect even on average across market participants. The motivation for considering this possibility is due to the fact that several recent policy events (achievement of Paris Agreement, outcome of US elections, the US withdrawal from Paris Agreement, Brexit, the outcome of 2018 Italian elections) have been incorrectly forecast by most observers and investors. Nevertheless, these events and their incorrect pricing are having long-lasting economic effects (see e.g. the spread on Italy' sovereign bonds). This implies that these effects could not be priced in by market participants, and this possibility should be considered in financial pricing models of sovereign bonds. Since the experience shows that the possibility that markets do not anticipate correctly policy events and their economic impact is material, we assume that the investor wants to include this possibility among her scenarios. For instance, the phasing out of coal based electricity plants could occur late on the policy agenda, behind the initially announced schedule (e.g. in Poland), in a situation where market players are thinking that it won't happen any longer. This implies that they do not discount correctly the future value of investments in the assets that have these plants as underlying.

Today, the information available to policy makers and market players on the trajectories of future values of economic sectors' market share comes mostly from IAMs. These are (partial or general) equilibrium models, calibrated on the recent state of the economy and climate targets, and provide trajectories in which the economy remains in equilibrium along any given trajectory. Thus, moving from a BAU to a climate policy scenario implies jumping from an equilibrium condition to another one. Moreover, the levels of output of the sectors of the economy must be consistent one with each other to reach again equilibrium conditions. The latter feature means that, for instance, a decrease in electricity generation based on coal has to be compensated by an increase in generation based on other sources to be consistent with the internal demand. This, in turn, affects the relative prices. Each trajectory is also consistent with a specific target in terms of GHG by 2050, and with a specific scenario on the status of international coordination on climate efforts (McCollum et al. 2018). The trajectories integrate also the estimates of climate change damages to physical assets in the economy by means of a climate module. There exists only a limited number (less than 10) of established IAM in the world, run by independent and internationally recognized scientific institutions. The models consider a common set of internationally agreed climate policies and emissions scenarios but differ in the way they define certain output variables and in the data used for the calibration (e.g. Kriegler et al. 2013, McCollum et al. 2018). There is a consensus in considering the IAMs' set of trajectories as the information set available today about the future economic impact of climate change. Nevertheless, it is increasingly recognized that such models have some limitations (e.g. in the computation of the trajectories and outputs) that relate to the model structure and behaviour, and can affect the policy relevance of the outcomes (see e.g. Battiston and Monasterolo 2018). In our model, the investor takes the trajectories across IAM models and scenarios as common information set. To simplify the analysis, and without loss of generality, we restrict the choice to two models (GCAM and WITCH) and four climate policy scenarios (see section 5).

4.4. Sovereign default conditions

Based on the motivations discussed in Section 2, we assume here that sovereign bonds are not risk-free but are instead defaultable (Duffie and Singleton 1999; Duffie et al. 2003). Following a stream of literature (Gray et al. 2007), we model the payoff of the defaultable sovereign bond as dependent on the ability of the sovereign to repay the debt out of its fiscal revenues accrued until the maturity. More in detail, the balance sheet of the sovereign entity is modelled as follows:

- Assets: net fiscal assets, i.e. the accrued value over time of tax revenues minus expenditures such as investments and subsides;
- Liabilities: debt securities issued as sovereign bonds with the same maturity.

Differently from Gray et al. 2007, we do not consider whether debt is issued in local or foreign currency, and we do not consider exchange rate risk.

The **sovereign default condition** is defined as the value of net fiscal assets at the maturity being smaller than the liabilities (i.e. the face value outstanding of bonds plus, possibly, the coupons):

$$A_j(T) < L_j \tag{1}$$

where T is the maturity, A_j is the value of net fiscal assets, and L_j are the liabilities of the issuer j.

In the context of climate change, there is a consensus among scholars and practitioners on the fact that markets and investors are not yet pricing in all the information available about climate-related financial risks (see section 2). Therefore, we relax the classic assumptions of efficient and frictionless markets that is needed in the Merton model (Merton 1974) to solve the pricing in closed form. Our goal here is to model the mechanism of the shock transmission channel from fiscal revenue to the value of the sovereign bond, in a market that is non necessarily efficient. In this regard, we consider the following parsimonious set of assumptions:

- Commodity prices are constant in the 3 years' shock duration.
- The asset value is observable only at the investment time t_0 and at the maturity T_j. [2]

---

[2] One way to infer the initial value of the asset from market values is to relating it to the market value of the liabilities at t_0.

- The value of the liabilities at T_j is known.
- The asset value at the maturity differs from the initial value because of two types of shocks: an idiosyncratic shock, and a climate policy shock.
- The idiosyncratic shock distribution at T_j is common knowledge, although individual shocks cannot be anticipated.
- Individual climate policy shock cannot be anticipated. The magnitude is known, and calculated from the IAMs trajectories (see Section 4.3, but the probability distribution is unknown (and thus represents a source of uncertainty).
- In a disorderly transition, investors assume that economic activities in renewable energy and low-carbon sectors increase in value, while economic activities in fossil fuels and high-carbon sectors decrease in value. In the absence of information of how idiosyncratic shocks and climate policy shocks interact, investors consider the two types of shocks as independent. Thus, the net effect of a climate policy shock is to shift the distribution of the idiosyncratic shocks to the left or to the right, depending on the weight of low-carbon sectors in the current composition of the Gross Value Added (GVA, see below).

In Section 4.6, we derive the expression of the default probability on the sovereign bond, conditional to a given climate policy scenario P, as a function of: the initial value of the assets, the face value of the liabilities, and the distribution of the idiosyncratic shocks. [3]

4.5. Impact of climate policy shock on macroeconomic conditions: energy and electricity sectors

We consider the contribution of a sector S to country j's net fiscal assets and how this can be affected by changes in the economic performance of the sector S, either negatively or

---

[3] In principle, if the climate policy shocks were assigned the same likelihood, i.e. they are considered to occur with a uniform probability, we can also write the unconditional probability of default. The same is true if policy shocks are assigned probability weights estimated from expert judgment.

positively. We then relate the performance of the sector to the change in its market share as a result of a disorderly climate policy transition scenario.

In a disordered transition, a climate policy shock affects the performance of sectors S via a change in economic activities' market share, cash flows and profitability, eventually affecting the Gross Value Added (GVA) of the sector. The climate policy shock is calculated at the sector, country and regional level. The country's GVA composition is available at NACE 2 digit level from official statistics (e.g. Eurostat). Negative shocks result from the policy impact on the GVA of sectors based on fossil fuels technology, while positive shocks result from the impact on the GVA of sectors based on renewable energy technology.

$$\mathrm{GVA}_{j,el|r} = \mathrm{GVA}_{j,el} \times \mathrm{Share}_{el|r} \tag{2}$$

where

$$\mathrm{GVA}_{j,el} = \text{Shock on GVA from electricity}, \tag{3}$$

$$\mathrm{Share}_{el|r} = \text{Share of GVA from renewable sources}. \tag{4}$$

The GVA of country j, GVA_j can be decomposed as follows:

$$\mathrm{GVA}_j = \mathrm{GVA}_{j,e|f} + \mathrm{GVA}_{j,el|f} + \mathrm{GVA}_{j,el|r} \tag{5}$$

where

$$\mathrm{GVA}_{j,e|f} = \text{Shock on GVA from primary energy fossil}, \tag{6}$$

$$\mathrm{GVA}_{j,el|f} = \text{Shock on GVA from secondary energy, electricity, fossil}, \tag{7}$$

$$\mathrm{GVA}_{j,el|r} = \text{Shock on GVA from secondary energy, electricity, renewable}. \tag{8}$$

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[4]. Indeed, a body of empirical literature has

---

[4] 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.

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' economic 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 its country.[5] 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. Let's consider two countries j_1 and j_2, with utility sectors S_{j_1} and S_{j_2}, each represented by a single firm. Each of the two firms has a certain composition of energy sources, i.e. an energy mix composed by coal, gas, hydropower, wind, solar photovoltaic (PV) etc. To simplify the reasoning, we only consider a business line of fossil-based power generation and a renewable energy-based power generation. Each business line contributes to the firm's profits.

Before the policy shock, the utility firm S_{j_1} has a larger share of power generation from renewable sources compared to the firm S_{j_2} in the other country. As a result of the policy shock, both countries align themselves from the BAU B to a climate policy scenario P. For the utility firms, this means that they move from a pre-shock energy mix to a post-shock energy mix, in which the renewable energy sources have a larger weight.

As a result of the change in energy mix, there is decrease in the profit of the fossil-based business line, denoted as $\pi_{\mathrm{Foss}}(S_j, P) < \pi_{\mathrm{Foss}}(S_j, B)$. This is because some of the active power plants have to be phased out before the end of their life time. This decrease in

---

[5] Notice that the value of the net fiscal assets of issuer j depends on the sum of the profits of firms that are fiscal residents in j. 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 tax revenues. This is a conservative assumption because when tax rates are progressive, if large firms' profits decrease substantially, then these firms would contribute proportionally less to the tax revenue of the country.

profit is related to the decrease of the value of carbon intensive assets, usually referred to as "stranded assets" (Caldecott 2018).

For the renewable-based business line, the same change in energy mix implies instead an increase in profits, denoted as $\pi_{\text{Ren}}(S_j, P) > \pi_{\text{Ren}}(S_j, B)$. Notice that the renewable-based business line of a country faces not only the domestic demand, previously satisfied by the fossil-based business line, but possibly also some of the foreign demand, in case the policy shock results in a decrease in capacity and supply of the utility sector of the other country. If before the policy shock the renewable energy firm S_{j_1} operates below its full capacity, after the policy shock it can increase generation up to the full capacity at no additional cost, thus increasing profit. Further, the firm can increase its profit by expanding its capacity, provided that the firm can finance the expansion of its power generation capacity and that construction time of the new plants is shorter than the duration of the process of alignment of the economy as a result of the policy shock. The net effect of the change in energy mix on the profit of a given sector depends on the pre-shock energy mix and the post-shock energy 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 country incurs in terms of public investments and subsidies related to sector S_j.

Modeling explicitly the profit of the firms, the public investments and the subsidies in sector S_j, as well as in all the other climate relevant sectors, would require to spell out many more details, such as the lifetime of the plants, the dynamics of supply and demand as well as the dynamics of productivity. This task is out of the scope of the present paper. The consideration discussed earlier in this section lead us to make the assumption 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.

We define a market share shock to sector S under the policy scenario P, estimated based on IAM model M, and denoted as $u_j(S,P,M)$, as follows:

$$u_j(S,P,M) = \frac{m_j(S,P,M) - m_j(S,B,M)}{m_j(S,B,M)}. \tag{9}$$

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:

$$\frac{\Delta A_j(S,P,M)}{A_j(S)} = \chi_S \, u_j(S,P,M), \tag{10}$$

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 IAM scenario database (Kriegler ea. 2013), considering combinations of two models M (i.e.: GCAM, WITCH) and four climate policy scenarios P, characterized by different Greenhouse Gases (GHG) emissions targets and way to achieve them [6].

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:

$$\frac{\Delta A_j(P,M)}{A_j} = \sum_S \frac{\Delta A_j(S,P,M)}{A_j(S)} \frac{A_j(S)}{A_j} = \sum_S \chi_S \, u_j(S,P,M) \frac{A_j(S)}{A_j}, \tag{11}$$

In principle, in our approach, the elasticity coefficient could be estimated empirically for the specific sectors of the sovereign issuers in the portfolio. In this work, the data to carry out this estimation was not available. Being our goal to provide an estimation of the upper

---

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

bounds of the magnitude of the shocks due to a given climate policy scenarios P (see section 5), where the shock is transmitted to the value of the sovereign bond via the change in sectors' market share, GDP and fiscal assets, we have assumed a value of χ constant and equal to 1 (typical empirical values range between 0.2 and 0.6).

4.6. Climate shock transmission to sovereign fiscal assets and default probability

In order to take into account the joint effect of the idiosyncratic shock and the shock associated with a climate policy scenario P, the agents model the assets $A_j(T_j)$ of the sovereign issuer j at time T_j as a stochastic variable described by the following equation,

$$A_j(T_j) = A_j(t_0) + \xi_j(T_j, P) + \eta_j(T_j), \tag{12}$$

where $A_j(t_0)$ is the value of the asset at time t_0, $\xi_j(T_j, P)$ is the shock observable at time T_j associated with the climate policy scenario P, and $\eta_j(T_j)$ is an idiosyncratic shock observable at time T_j. In line with Gray ea. 2007, the issuer defaults at time T_j, if her assets at the maturity are lower than her liabilities, as a result of the two shocks, i.e.

$$A_j(t_0) + \xi_j(T_j, P) + \eta_j(T_j) < L_j \tag{13}$$

where the value of the liability L_j is assumed to be independent of the climate policy scenario P and of the time.[7]

In this formulation, for a given policy shock $\xi_j(T_j, P)$, the conditioned default probability of the issuer is the probability that the idiosyncratic shock η_j at time T_j is smaller than a threshold value $\theta_j(P)$, which depends on issuer j's liability and initial asset value at time t_0, and on the magnitude of the climate policy shock ξ_j on the asset side. Formally, the default condition reads:

$$\eta_j(T_j) < \theta_j(P) = -\xi_j(T_j, P) - A_j(t_0) + L_j \tag{14}$$

In case of no policy shock, ξ_j equals 0 and the default condition becomes:

$$\eta(T_j) < \theta_j(B) = -A_j(t_0) + L_j. \tag{15}$$

---

[7] This means that the debt cannot be restructured or repurchased by the issuer.

Notice that the values of the thresholds differ by the magnitude of the policy shock:

$$\theta_j(P) = \theta_j(B) - \xi_j(T_j, P). \tag{16}$$

The default probability in absence of the policy shock, i.e. in the business as usual (BAU) scenario is:

$$q(B) = \mathcal{P}(\eta_j < \theta_j(B)) = \int_{\eta_{\text{inf}}}^{\theta_j(B)} \phi(\eta_j)\, d\eta_j, \tag{17}$$

where $p(\eta_j)$ is the probability distribution of the idiosyncratic shock η_j, and η_{inf} is the lower bound of the support of the probability distribution. In contrast, the default probability in the case of policy shock P is:

$$q(P) = \mathcal{P}(\eta_j < \theta_j(P)) = \int_{\eta_{\text{inf}}}^{\theta_j(P)} \phi(\eta_j)\, d\eta_j = \int_{\eta_{\text{inf}}}^{\theta_j(B)-\xi_j(T_j,P)} \phi(\eta_j)\, d\eta_j.$$

The difference between the value of the threshold from BAU to P, i.e. $-\xi_j(T_j, P)$ has a negative sign because it reflects the fact that if the policy shock is negative, default threshold becomes larger and so does the default probability. Now, the *change* in default probability due to a climate policy shock (i.e. a disorderly transition to a given climate scenario P), relative to the case of no policy shock B is

$$\Delta q(P) = q(P) - q(B) = \int_{\eta_{\text{inf}}}^{\theta_j(P)} \phi(\eta_j)\, d\eta_j - \int_{\eta_{\text{inf}}}^{\theta_j(B)} \phi(\eta_j)\, d\eta_j. \tag{18}$$

We then have

$$\Delta q(P) = \int_{\theta_j(B)}^{\theta_j(P)} \phi(\eta_j)\, d\eta_j = \int_{\theta_j(B)}^{\theta_j(B)-\xi_j(T_j,P)} \phi(\eta_j)\, d\eta_j. \tag{19}$$

Notice that the change in default probability depends on the policy shock $\xi_j(T_j, P)$ because it appears in the lower bound of the integral.[8] In order to understand the impact of the shock on the default probability consider the case of a negative shock on fiscal asset $\xi_j(T_j, P) < 0$. The larger, in magnitude, is the shock, the larger is the upper extreme of the integral, and hence the larger is the increase in default probability, resulting from the policy shock P.

---

[8] Since all shocks are computed as difference from the same scenario B to the various scenarios P, we drop the dependence from B.

In the previous section we have modelled the policy shock as $\xi_j(T_j, P)$ as a shock on the fiscal assets of the issuer. Consistently, we interpret now the shock as $\xi_j(T_j, P) = \frac{\Delta A_j(P,M)}{A_j(P,M)}$. In virtue of Eq. 11, the shock can be expressed as sum of the shocks on the economic sectors of the economy j as follows:

$$\xi_j(T_j, P) = \frac{\Delta A_j(P, M)}{A_j(P, M)} = \sum_S \chi_S \, u_j(S, P, M) \frac{A_j(S)}{A_j}. \tag{20}$$

4.7. Climate shock's introduction in the pricing of defaultable sovereign bonds

Based on the motivations discussed in Section 2, we consider a defaultable sovereign bond issued at time t_0 and with maturity T. For the sake of simplicity we illustrate the derivation in the basic standard case of a zero-coupon bond with constant risk free rate, constant yield and with exogenous recovery rate R_j.

We denote the default probability as $q = \mathcal{P}(\tau < T)$, where τ is the time of default. In case of default, the bond pays a recovery rate R_j, defined as fraction of its face value. The expected unitary value of the bond at t_0 can be written as

$$v_j = e^{-r_f \, (T-t_0)}(1 - q_j + q_j \, R_j) \tag{21}$$

where r_f is the risk free rate. The yield of the bond is defined as

$$r_j = -\frac{1}{(T - t_0)} \log(1 - q_j(1 - R_j)). \tag{22}$$

The spread of the bond is the difference between the bond yield and the risk free rate $r_j - r_f$.

In the previous sections, we have modelled how the the climate policy shock affects the default probability of the defaultable bonds. Here, we can now derive its impact on the expected value of the bond and on its yield.

On the one hand, there is no established model to account for a risk premium for climate policy shocks. On the other hand, there is ambiguous evidence that so far markets have been pricing climate risk across instruments and asset classes.

The change in yield can be considered a non-decreasing function f of the climate policy shock ξ as follows:

$$\Delta r_j(P) = r_j(q(P)) - r_j(q(B)) = -f_r(\xi_j(T_j, P)). \tag{23}$$

The minus sign highlights the direction of the relationship. Indeed, based on the assumptions in the model, f_r is non decreasing, since a negative climate policy shock $\xi_j(T_j, P)$ does not decrease the default probability q and thus does not decreases yield.

A similar relation holds for the change in value of the bond,

$$\begin{aligned}\Delta v_j(P) &= v_j(q(P)) - v_j(q(B)) = e^{-r_f\,(T-t_0)}(1 - q_j + q_j\,R_j) \\ &= -\,e^{-r_f\,(T-t_0)}(q_j(P) - q(B))(1 - R_j) = \qquad (24) \\ &= f_v(\xi_j(T_j, P)). \qquad (25)\end{aligned}$$

We do not aim here to calibrate Equations 23 and 31, as this would require to estimate the probability distribution ϕ of the idiosyncratic shocks on net fiscal assets in Equation 4.6. It is also known that estimating sovereign default probability is problematic because the default is a rare event compared to the available time series. The aim of the paper, at this stage, is carry out some estimations of the impact of the climate policy shock on a bond portfolio based on scenarios.

4.8. Climate VaR of a sovereign bond portfolio

In the previous section we have developed a simple quantitative model of how a future climate policy shock (due to a disorderly low-carbon transition) can impact on the yield and the expected value of a sovereign bond, through the channel of its intermediate impact on the sovereign net fiscal assets and its default probability.

We have distinguished the nature of the policy shock from that of the daily shocks on the bond market price, which can seen as reflecting the daily adjustments in how the market as a whole assesses the future fundamentals of the economy and the sovereign risk, without accounting for the policy shock.

In the absence of information on how the climate policy and the shocks on market value interact, we consider the two processes as independent. This is motivated by the fact there is little evidence of markets having priced in climate policy risk in their evaluation so far and the fact that we are considering a climate policy shock that leads to a disorderly alignment of the economy. Given this information set and market conditions, an investor can only approximate the distribution of future bond market values as the one of today plus the effect of climate policy shock.

We leave for future work to investigate whether it can be proved formally that, given the information set, this approximation of the distribution of the sovereign bond value is an optimal assessment, under some statistical objectives of likelihood.

We can thus express the value of the bonds portfolio as follows:

$$\sum_{j} Z_j(v_j(1+x_j)+\Delta v_j(P)), \tag{26}$$

where Z_j is the numeraire amount invested at time t_0 in each bond (at the market value of t_0), v_j is the market unitary value of the bond at t_0, x_j is the shock on market value at $t_0 < t < T$, $\Delta v_j(P)$ is the change in expected value of the bond that would be caused by a climate policy shock P.

Definition *The Value at Risk of the portfolio is defined as the value such that the following expression holds:*

$$\int^{VaR} dx_1, ...dx_j, ..., dx_n\, \psi(x_1, ..., x_j, ..., x_n) \sum_{j=1,...,n} Z_j\left(v_j(1+x_j)+\Delta v_j(P)\right) = c_{VaR}, \tag{27}$$

where c_{VaR} is the confidence level (usually set between 0.5% and 5%), $\psi(x_1, ..., x_j, ..., x_n)$ is the joint probability distribution of shocks on sovereign market prices.

Notice that joint probability distribution captures the fact that sovereign market prices can be highly correlated in certain times (as it happened in 2012).

Our model shows that there are strong reasons to expect that a disordered climate transition (and thus a climate policy shock) would impact the coupon rate and thus the value of a sovereign bond. However, to our knowledge, based on the literature review performed in Section 2, there is no empirical literature on the relation described in Equation 23. Even the literature on the drivers of sovereign coupon rate in general, outside the context of climate risk, can't provide conclusive evidence.

One strategy to carry out a risk analysis in the face of the limited information available is to consider a first order approximation of Equation 23:

$$\Delta r_j(P) = -f(\xi_j(T_j, P)) \approx -(f(0) + f'(0) \sum_S \chi_S \, u_j(S, P, M) A_j(S)), \tag{28}$$

as a Taylor expansion (see eq. 13), and to consider a scenario in which:

$$\Delta r_j \approx -\frac{\xi_j(T_j, P)}{A_j} = -\sum_S \chi_S \, u_j(S, P, M) \frac{A_j(S)}{A_j}. \tag{29}$$

$$\Delta r_j \approx -\frac{\xi_j(T_j, P)}{A_j} = -\sum_S \chi_S \, u_j^{\mathrm{GVA}}(S, P, M) \, \frac{\mathrm{GVA}_j(S)}{\mathrm{GVA}_j}. \tag{30}$$

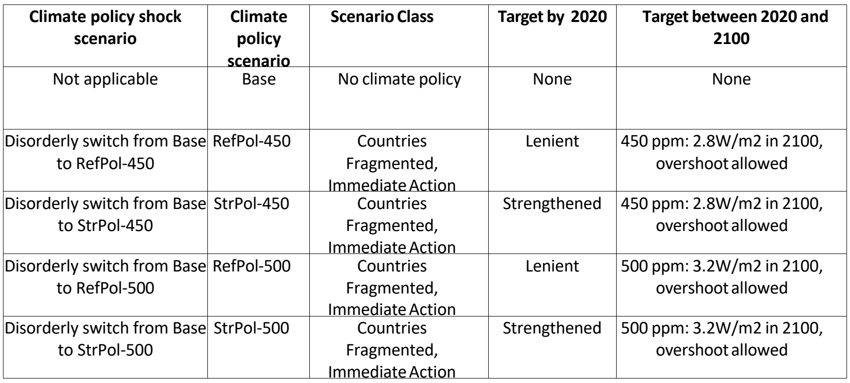
We then compute the change in value of the bond as

$$\begin{aligned}
\Delta v_j(P) =& \, e^{-r_f \, (T-t_0)}((1 - q_j(P))e^{r_j(P) \, (T-t_0)} + q_j(P) \, R_j) + & (31)\\
& - e^{-r_f \, (T-t_0)}((1 - q_j(B))e^{r_j(B) \, (T-t_0)} + q_j(B) \, R_j) = & (32)\\
\approx & \, e^{-r_f \, (T-t_0)} e^{r_j(P) \, (T-t_0)} - e^{-r_f \, (T-t_0)} e^{r_j(B) \, (T-t_0)} = & (33)\\
= & \, e^{-r_f \, (T-t_0)} \big(e^{(r_j(B)+\Delta r_j(P)) \, (T-t_0)} - e^{r_j(B) \, (T-t_0)}\big) = & (34)\\
= & \, e^{-r_f \, (T-t_0)} e^{r_j(B)(T-t_0)} (e^{\Delta r_j(P)} - 1). & (35)
\end{aligned}$$

Notice that the approximation in the third passage is carried out for small values of $q_j(B)$ and $q_j(P)$. To calibrate the above expression, one can estimate $r_j(B)$ as the current market value of the coupon rate at t_0. Since the policy shock has not occurred yet in the real world, this is indeed the scenario B. Finally the term $\Delta r_j(P))$ is taken from the previous Equation 30.

5. Climate policy scenarios and shock trajectories

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 degrees C target from the LIMITS database and a baseline of no climate policy, described in Table 1. We use the LIMITS project database (Kriegler et al. 2013) to compute the trajectories of the market shares for several variables including the output of primary energy from fossil fuel and the output of secondary energy in the form of electricity both from fossil fuel sources and renewable energy sources. 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 degrees C aligned IPCC scenarios (IPCC 2014). The 500 and 450 ppm scenarios are associated to a probability of exceeding the 2 degrees 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.



Climate policy shock scenario	Climate policy scenario	Scenario Class	Target by 2020	Target between 2020 and 2100
Not applicable	Base	No climate policy	None	None
Disorderly switch from Base to RefPol-450	RefPol-450	Countries Fragmented, Immediate Action	Lenient	450 ppm: 2.8W/m2 in 2100, overshoot allowed
Disorderly switch from Base to StrPol-450	StrPol-450	Countries Fragmented, Immediate Action	Strengthened	450 ppm: 2.8W/m2 in 2100, overshoot allowed
Disorderly switch from Base to RefPol-500	RefPol-500	Countries Fragmented, Immediate Action	Lenient	500 ppm: 3.2W/m2 in 2100, overshoot allowed
Disorderly switch from Base to StrPol-500	StrPol-500	Countries Fragmented, Immediate Action	Strengthened	500 ppm: 3.2W/m2 in 2100, overshoot allowed

Table 1 describes some characteristics of the five climate policy scenarios from the LIMITS database (Kriegler et al. 2013) that were used for the calculations: Base scenario, RefPol-450, RefPol-500, StrPol-450, StrPol-500.

A change in climate policy (i.e. in the value of the carbon tax every 5-years time step) implies a change in the sectors' macroeconomic trajectory, and thus a change in the market share of primary and secondary energy sources. In a scenario characterised by a disorderly transition, the carbon tax would not be fully anticipated by the firms and investors and thus prices and markets would not fully adjust. The shock in the market share could differ in sign and magnitude depending on the scenario S, the region R, the model M used and the sector S. We consider a shock occurring in 2030, affecting the market shares of the sectors to which OeNB's portfolio is exposed via sovereign bonds.

6. Data

In this section, we present the datasets used for our analysis.

6.1. OeNB's portfolio holdings dataset

OeNB's portfolio contains 1386 entries as of June 2018. Exposures to sovereign bonds represents the majority of the holdings, 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. We have excluded the contracts with missing code from the analysis.

6.2. Classification of sectors of economic activity

The classification of economic sectors NACE Rev2 at 4-digits (Nomenclature statistique des activités économiques dans la Communauté européenne) by Eurostat provides a detailed well-established taxonomy of economic activities that is widely used in EU for policy purposes. NACE sectors are listed from A—Agriculture, forestry, and fishing to U - Activities of extraterritorial organizations and bodies. 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. However, one important limitation comes from the fact that the Eurostat classification of economic sectors (NACE Rev2) was designed for national accounting purposes in a time when climate and sustainability considerations were not considered. As a result, the economic activities are not grouped in sectors that are relevant for the analysis of the impact of the low-carbon transition. For instance, some oil companies are classified under Manufacturing while others under Mining and Quarrying. We address this challenge by carrying out a remapping of the subsectors in 5 sectors that are more relevant for policy purposes (see Battiston et al. 2017).

6.3. 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, and by the IEA's World Energy Outlook (2018). We use data on energy electricity production by source and country to estimate the gross value added of each technology and its share on total electricity production by country. This information is then used to weigh the impact of climate policy shock on the climate spread and on the sovereign bonds' value.

7. 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. We considered, 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.

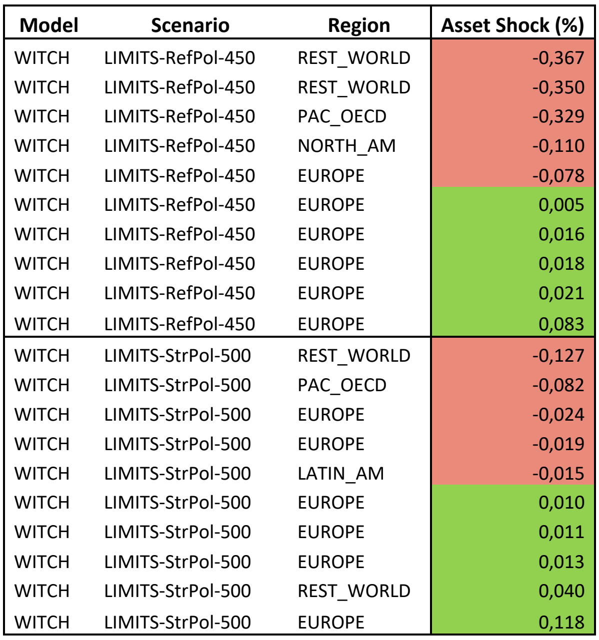
Table 2 shows the impact of climate policy shocks on the value of sovereign bonds and sovereign bonds' yields, i.e. the climate spread, computed with two LIMITS' IAMs, i.e.

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.

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' 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.

8. Conclusion

Aligning finance to sustainability requires to embed climate risks and their characteristics (forward-looking, deep uncertainty, non-linearity, endogeneity) in financial risk pricing metrics and methods used by academics, investors and financial supervisors. In this paper, we contribute to fill this gap by developing a methodology for the quantitative assessment of forward-looking climate transition risks in the value of financial contracts, thus complementing traditional financial pricing models. The manuscript presents the theoretical background and the application of the CLIMAFIN methodology to the sovereign bonds of OECD countries that are included in the non-monetary policy portfolio of the OeNB.

Our framework considers a risk averse investor with an information set composed of future climate scenarios (but no probability of occurrence associated), economic trajectories conditioned to the climate policy scenarios, and historic values of data on financial performance of low-carbon and carbon-intensive firms and sectors. Then, it combines prudential policies that don't require probabilities (e.g. min-max valuation) with financial risk measures (e.g. Value at Risk and Spread) applied to variables for which estimates of probabilities are available. This allows to make decisions retaining the variability in information set, considering investor's risk aversion and/or uncertainty.

In particular, we develop:

- The formalization of a model that allows to price climate transition scenarios developed by IAMs (Kriegler et al. 2013, McCollum et al. 2018) in the value of individual sovereign bonds via shocks on GVA and fiscal revenues;
- The introduction of the notion of Climate sovereign Spread and its empirical assessment;
- The computation of overall gains or losses for an investor (in this case, OeNB)'s portfolio conditioned to climate transition risk, considering disorderly transition scenarios.

We find that the countries' and credibility of the introduction of climate policies matter for countries' economic competitiveness and financial stability. Indeed, countries that started earlier to align their economy to the climate targets, obtain a strengthened fiscal and financial position, and negative climate-related yields on the sovereign, i.e. the *climate spread.* In contrast, countries where the fossil fuel sector represent a large (both directly or indirectly) contributes revenues derive directly or indirectly from fossil fuel based energy production or consumption, have a positive climate spread and thus higher yields on the sovereign. This, in turn, negatively affects the value of the sovereign portfolio of investors exposed to such countries.

We would like to point out that our shock results should be considered as conservative for the following reasons. First, for each sovereign bond, the negative shocks (e.g. on primary energy fossil) can be compensated by positive shocks (e.g. electricity based on renewable sources). Second, for each portfolio, the negative aggregate shocks stemming from a less climate-aligned sovereign can be compensated by positive shocks from more climate-aligned sovereign. Third, in this application we do not consider the macroeconomic reverberations of a shock (either positive or negative). Further, we use climate policy trajectories provided by IAMs that recent studies (IPCC 2018) consider not sufficient to achieve the Paris Agreement targets. Finally, in assessing the impact of the shock on the financial risk and stability of a financial institution, we should consider its financial risk characteristics, starting from its leverage ratio.

Our approach can help investors and financial supervisors to assess the conditions for the onset of systemic risks in financial markets, and to inform portfolios' rebalancing strategies and risk mitigation measures.

9. References

Ackerman, F. (2017). Worst-Case Economics: Extreme Events in Climate and Finance. Anthem Press.

Arellano, C. (2008). Default risk and income fluctuations in emerging economies. *American Economic Review*, 98(3), 690-712.

Attinasi, M. G., Checherita-Westphal, C. D., Nickel, C. (2009). What explains the surge in euro area sovereign spreads during the financial crisis of 2007-09?. European Central Bank Working Papers Series, No. 1131.

Battiston, S., Jakubik, P., Monasterolo, I., Riahi, K. and van Ruijven, B. (2019). Climate risk assessment of the sovereign bond portfolio of European insurers. In: European Insurance and Occupational Pension Fund (EIOPA) Financial Stability Report, pp. 69-89, December, 2019.

Battiston, S., Monasterolo, I. (2019). How could the ECB's monetary policy support the sustainable finance transition? FINEXUS working paper (input to the Positive Money and Veblen's policy report "Aligning Monetary Policy with the EU's Climate Targets") https://www.finexus.uzh.ch/en/news/cspp$_s ustainable_f inance.html$

Battiston, S., Monasterolo, I. (2018). The Climate Target Gap Is Widening. Can We Close It by Including Climate Finance in SSPs? (October 14, 2018). Available at SSRN: https://ssrn.com/abstract=3266041 or http://dx.doi.org/10.2139/ssrn.3266041

Battiston, S., Mandel, A., Monasterolo, I., Schütze, F., Visentin, G. (2017). A Climate Stress-test of the Financial System. *Nature Climate Change*, 7(4), 283–288. https://doi.org/10.1038/ncl

Battiston, S., Caldarelli, G., May, R. M., Roukny, T., Stiglitz, J. E. (2016). The price of complexity in financial networks. *Proceedings of the National Academy of Sciences*, 113(36), 10031-10036.

Battiston, S. (2019). The importance of being forward-looking: managing financial stability in the face of climate risk. In: Financial Stability Review Banque de France, June 2019 https://publications.banque-france.fr/en/liste-chronologique/financial-stability-review

Berger, L., Emmerling, J., Tavoni, M. (2016). Managing catastrophic climate risks under model uncertainty aversion. *Management Science*, 63(3), 749-765.

Black, F., Cox, J. C. (1976). Valuing corporate securities: Some effects of bond indenture provisions. *The Journal of Finance*, 31(2), 351-367.

Black, F., Scholes, M. (1973). The pricing of options and corporate liabilities. *Journal of Political Economy*, 81(3), 637-654.

Borensztein, E., Panizza, U. (2009). The costs of sovereign default. IMF Staff Papers, 56(4), 683-741.

Broner, F., Martin, A., Ventura, J. (2006). Sovereign risk and secondary markets (No. w12783). *National Bureau of Economic Research.*

Caldecott, B. (Ed.). (2018). Stranded Assets and the Environment: Risk, Resilience and Opportunity. Routledge.

de Greiff, K., Delis, M., Ongena, S. (2018). Being stranded on the carbon bubble? Climate policy risk and the pricing of bank loans. CEPR Discussion Papers (May 2018).

Dosi, G., Roventini, A. (2019). More is different... and complex! the case for agent-based macroeconomics. *Journal of Evolutionary Economics* 29(1), 1-37

Drouet, L., Bosetti, V., Tavoni, M. (2015). Selection of climate policies under the uncertainties in the Fifth Assessment Report of the IPCC. *Nature Climate Change*, 5(10), 937.

Duffie, D., Singleton, K. J. (1999). Modeling term structures of defaultable bonds. *The Review of Financial Studies*, 12(4), 687-720.

Duffie, D., Pedersen, L. H., Singleton, K. J. (2003). Modeling sovereign yield spreads: A case study of Russian debt. *The Journal of Finance*, 58(1), 119-159.

Dunz, N., Naqvi, A., Monasterolo, I. (2019). Climate Transition Risk, Climate Sentiments, and Financial Stability in a Stock-Flow Consistent approach. *Ecological Economic Papers*, 23. WU Vienna University of Economics and Business, Vienna.

Eaton, J. (1996). Sovereign debt, reputation and credit terms. *International Journal of Finance Economics*, 1(1), 25-35.

Ehlers, T., Packer, F. (2017). Green bond finance and certification. BIS Quarterly Review September.

ESRB (2016). Too Late, too Sudden: Transition to a Low-carbon Economy and Systemic Risk (No. 6). European Systemic Risk Board.

Favero, C., Pagano, M., Von Thadden, E. (2010). How does liquidity affect government bond yields. *Journal of Financial and Quantitative Analysis* 45, 107–134.

Farmer, J. D., Hepburn, C., Mealy, P., Teytelboym, A. 2015. A third wave in the economics of climate change. *Global Environmental Change* 62(2), 329-357.

Gray, D. F., Merton, R. C., Bodie, Z. (2007). New framework for measuring and managing macrofinancial risk and financial stability (No. w13607). *National Bureau of Economic Research.*

Greenwald, B. C., Stiglitz, J. E. (1986). Externalities in economies with imperfect information and incomplete markets. *The Quarterly Journal of Economics*, 101(2), 229-264.

Hallegatte, S., Shah, A., Lempert, R., Brown, C., Gill, S. (2012). Investment decision making under deep uncertainty-application to climate change. The World Bank.

High-Level Experts Group on Sustainable Finance (HLEG) (2017). Financing a Sustainable European Economy. Interim Report, July 2017.

Intergovernmental Panel on Climate Change (IPCC) (2014). Climate Change 2014 Synthesis Report. Fifth Assessment Report (AR5). Retrieved from https://www.ipcc.ch/report/ar5/syr/

Karpf, A., Mandel, A. (2018). The Changing Value of the 'Green' Label on the US Municipal Bond Market. *Nature Climate Change*, 8(2), 161.

Keynes, J. M. (1973). The Collected Writings of John Maynard Keynes. Vol. 8 (A Treatise on Probability). London: MacMillan for the Royal Economic Society.

Kletzer, K. M., Wright, B. D. (2000). Sovereign debt as intertemporal barter. *American economic review*, 90(3), 621-639.

Kling, G., Lo, Y. C., Murinde, V., Volz, U. (2018). Climate Vulnerability and the Cost of Debt. SOAS working paper. Available at SSRN: https://ssrn.com/abstract=3198093 or http://dx.doi.org/10.2139/ssrn.3198093

Knight, F. H. (1921). Risk, Uncertainty, and Profit. Boston: Houghton Mifflin Co, 210-235.

Kriegler et al . (2013) What does the 2 C target imply for a global climate agreement in 2020? The LIMITS study on Durban Platform scenarios. *Climate Change Economics* 4, 1340008.

Kriegler, E., Hall, J. W., Held, H., Dawson, R. Schellnhuber, H. J. (2009). Imprecise probability assessment of tipping points in the climate system. *Proc. Natl Acad. Sci.* 106, 5041–5046.

Lamperti, F., Monasterolo, I., Roventini, A. (2019). Climate Risks, Economics and Finance: Insights from Complex Systems. In The Systemic Turn in Human and Natural Sciences (pp. 97-119). Springer, Cham.

Lemmen, J. J., Goodhart, C. A. (1999). Credit risks and european government bond markets: a panel data econometric analysis. *Eastern Economic Journal*, 25(1), 77-107.

Leaton, J. 2012. Unburnable Carbon—Are the World's Financial Markets Carrying a Carbon Bubble?. Carbon Tracker Initiative.

Lemoine, D. Traeger, C. P. 2016. Economics of tipping the climate dominoes. *Nature Climate Change* 6.

Lenton, T.M., Rockström, J., Gaffney, O., Rahmstorf, S., Richardson, K., Steffen, W. and Schellnhuber, H.J. (2019). Climate tipping points—too risky to bet against. *Nature*, 592-595.

McCollum, D. L., Zhou, W., Bertram, C., de Boer, H. S., Bosetti, V., Busch, S., ... Fricko, O. (2018(. Energy investment needs for fulfilling the Paris Agreement and achieving the Sustainable Development Goals. *Nature Energy* 1.

Merton, R. C. (1974). On the pricing of corporate debt: The risk structure of interest rates. *The Journal of Finance*, 29(2), 449-470.

Monasterolo, I., Battiston, S., Janetos, A. C. A. C., Zheng, Z. (2017). Vulnerable yet relevant: the two dimensions of climate-related financial disclosure. *Climatic Change*, 145(3–4), 495–507.

Monasterolo, I., De Angelis, L. (2020). Blind to carbon risk? An analysis of stock market reaction to the Paris Agreement. *Ecological Economics*, 170, 1-9.

Morana, C., Sbrana, G. (2018). Some financial implications of global warming: an empirical assessment (Febr. 2018). Working Paper.

Mukanjari, S., Sterner, T. (2018). Do markets trump politics? Evidence from fossil market reactions to the Paris Agreement and the US election. Working Paper.

Nalebuff, B. J., Stiglitz, J. E. (1983). Information, competition, and markets. *The American Economic Review*, 73(2), 278-283

Network for Greening the Financial System. (NGFS). Retrieved September 12, 2018, from https://www.banque-france.fr/en/financial-stability/international-role/network-greening-financial-system

Oliveira, L., Curto, J. D., Nunes, J. P. (2012). The determinants of sovereign credit spread changes in the Euro-zone. Journal of International Financial Markets, Institutions and Money, 22(2), 278-304.

Panizza, U., Sturzenegger, F., Zettelmeyer, J. (2009). The economics and law of sovereign debt and default. *Journal of Economic Literature*, 47(3), 651-98.

Pindyck, R. S. Climate Change Policy: What Do the Models Tell Us? (2013). *NBER* Working Paper Series, 51, 1–23.

Ramelli, S, A F Wagner, R J Zeckhauser, and A Ziegler (2019). Stock price rewards to climate saints and sinners: Evidence from the Trump election. *NBER* working paper 13206.

Sandleris, G. (2008). Sovereign defaults: Information, investment and credit. *Journal of international Economics*, 76(2), 267-275.

Sharpe, W.F. (1964) Capital Asset Prices: A Theory of Market Equilibrium Under Conditions of Risk. *Journal of Finance* 19(3), 425-442

Solomon S., Plattner GK., Knutti R., and Friedlingstein P. (2009). Irreversible climate change due to carbon dioxide emissions.*Proceedings of the National Academy of Sciences* (PNAS)10, 2009106(6)1704 − 1709;*https* : //*doi.org*/10.1073/*pnas*.0812721106

Steffen, W., Rockström, J., Richardson, K., Lenton, T. M., Folke, C., Liverman, D., ... Schellnhuber, H. J. (2018). Trajectories of the Earth System in the Anthropocene. *Proceedings of the National Academy of Sciences* (*PNAS*), 115(33), 8252–8259. https://doi.org/10.10

Stern N. (2008). The economics of climate change. *American Economic Review* 98(2), 1-37.

Weitzman, M. L. (2009). On modeling and interpreting the economics of catastrophic climate change. *The Review of Economics and Statistics*, 91(1), 1-19