CLIMATE RISK ASSESSMENT OF THE SOVEREIGN BOND PORTFOLIO OF EUROPEAN INSURERS[40]

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ABSTRACT

In the first collaboration between climate economists, climate financial risk modellers and financial regulators, we apply the CLIMAFIN framework described in Battiston at al. (2019) to provide a forward-looking climate transition risk assessment of the sovereign bonds' portfolios of solo insurance companies in Europe. We consider a scenario of a disorderly introduction of climate policies that cannot be fully anticipated and priced in by investors. First, we analyse the shock on the market share and profitability of carbon-intensive and low-carbon activities under climate transition risk scenarios. Second, we define the climate risk management strategy under uncertainty for a risk averse investor that aims to minimise her largest losses. Third, we price the climate policies scenarios in the probability of default of the individual sovereign bonds and in the bonds' climate spread. Finally, we estimate the largest gains/losses on the insurance companies' portfolios conditioned to the climate scenarios. We find that the potential impact of a disorderly transition to low-carbon economy on insurers portfolios of sovereign bonds is moderate in terms of its magnitude. However, it is non-negligible in several scenarios. Thus, it should be regularly monitored and assessed given the importance of sovereign bonds in insurers' investment portfolios.

1. INTRODUCTION

The topic of sustainable finance has gained attention among European insurers and the financial supervisory community alike. This is fuelled by recent initiatives promoted by

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financial supervisors, central banks and policy makers to align finance to sustainability. For instance, in 2018 several international central banks and financial regulators launched the Central Banks and Financial Regulators' Network for Greening the Financial System (NGSF 2018). In 2019, the European Commission (EC) launched the "Action Plan on Sustainable Finance" to tackle climate related risks and achieve the long-term goal of economic transformation towards a low-carbon economy. These initiatives are aimed to mitigate the potential financial risks stemming from a disorderly low-carbon transition, by supporting the alignment of investments to the climate targets.

Limiting the global temperature increase to 2°C above pre-industrial levels (i.e. consistently with Paris Agreement, UNFCCC 2016) requires the timely and coordinated introduction of climate policies, e.g. a global carbon tax (Stiglitz et al., 2017; IMF, 2019) aimed to drastically decrease the CO_2 emissions produced by the combustion of fossil fuels in the economy.

However, governments are delaying in the introduction of climate policies, leading potentially to a disorderly transition, where the introduction of climate policies is sudden and cannot be fully anticipated and priced in by investors (Battiston et al., 2017). In this context, firms whose revenues depend directly or indirectly on use of fossil fuels energy and electricity could face significant losses (the so-called "carbon stranded assets", Leaton et al. 2012). These losses will affect the value of the financial contracts issued by such firms and cascade onto their investors (Battiston et al., 2017), with implications on price volatility if large and correlated asset classes are involved (Monasterolo et al., 2017), and on firms and countries' financial stability (Battiston and Monasterolo, 2019). In this respect, not only climate related exposures of insurance firms towards the corporate sector but also towards the sovereigns in which those activities take place could be negatively affected. Given the role of the insurance sector in the economy and finance, the exposure of insurance firms to climate-related financial risks deserve to be monitored and assessed.

A main obstacle for insurers to embed climate in their portfolios' risk management strategies is represented by the lack of appropriate methodologies to price forward-looking climate risks and opportunities in the value of individual financial contracts and in the probabilities of default of investors portfolios. The reason is that climate risks are forward-looking (because they refer to future occurrences), characterised by deep uncertainty (thus leading to fat tailed distributions, Weitzman, 2009), non-linearity (Ackerman, 2017), and endogeneity that could give rise to multiple equilibria (Battiston et al., 2017). These characteristics makes the reliance on historical data much less relevant for risk assessment. This means that climate transition risks cannot be priced based on historical market data (e.g. to calculate volatility measures), but require to use the information on future climate policy shocks produced by climate economic models (e.g. Integrated Assessment Models - IAMs), and to introduce climate ambiguity.

Nevertheless, traditional financial pricing models (e.g. Merton, 1974; Black and Scholes, 1973; Black and Cox, 1976; Duffie and Singleton, 1999) are not able by construction to embed the characteristics of climate risks. Indeed, their financial risk assessment is based on past firms' performance (e.g. the computation of volatility measures based on historical data). In addition, they are constrained by conditions of normal distributions, complete markets, and lack of arbitrage (Battiston and Monasterolo, 2019).

Thus, pricing climate in investors' portfolio requires to move from the backward-looking nature of traditional financial risk assessment and of investors' benchmarks to a forward-looking assessment of risk. In this paper, we develop an application of the CLIMA-

FIN framework (Battiston et al., 2019) to calculate the probability of default of sovereign bonds, portfolio's financial risk metrics (e.g. the Climate Spread), and the largest losses/ gains on insurers' portfolios conditioned to future climate transition shocks. This analysis represents the first climate-financial risk assessment developed in collaboration between scientists of the climate economic community that informs the Intergovernmental Panel on Climate Change (IPCC), climate financial risk experts and a financial regulatory institution with a mandate to contribute to financial stability.

We build on CLIMAFIN, because it is the first approach to combine forward-looking climate transition risk shocks and associated economic trajectories based on We build on CLIMAFIN because it is the first approach to combine forward-looking climate transition risk scenarios and associated economic trajectories based on climate economic models, with financial pricing models and financial risk metrics. In addition, CLIMAFIN provides a transparent and robust methodology for climate financial risk assessment under deep uncertainty, by considering the characteristics of climate risks and of financial risks.

In this application, we build on the LIMITS[45] database of climate policy scenarios (Kriegler et al., 2013). These models are the reference for scientific community and the IPCC, with climate financial risk metrics and methods that are now a reference in both the academic and practitioners' community, i.e. the Climate Spread, the Climate VaR, climate financial pricing models and financial network-based Climate Stress-tests (Battiston et al., 2017). In the context of potentially destabilizing financial impact of a disorderly climate transition and of unmitigated climate change, transparent and robust methodologies can support financial supervisors' policy decisions to align finance to sustainability and climate targets while preventing financial instability.

This article is organized as follows. Section 2 elaborates on the relevant literature. Section 3 provides a description of the data sample used and the section 4 describes the CLIMAFIN methodology for pricing forward-looking climate transition risks in the value of sovereign bonds and in investors' portfolios. The results of empirical analysis conducted on the portfolios of EU insurance companies are presented in section 5, while section 6 concludes discussing the linkages with the next steps of this research into the Climate Stress-test.

2. LITERATURE REVIEW

Recent research suggest that climate risks (and opportunities) are not properly priced yet in the value of financial contracts and thus, in investor portfolios' risk management strategies. This means that investors might, on the one hand, increase (and trade) their exposure to climate risks, and on the other hand, they might delay the scaling-up of green investments.

The literature has mostly covered corporate debt contracts, only recently the attention has focused on sovereign bonds and equity holdings. Alessi et al. (2019), Zerbib (2019) and Karpf and Mandel (2018) assessed if a green bonds' premium exists in the bond market, but found very different results, based on the type of bonds contract analysed and the "green" definition used. In the catastrophe bonds (CAT) market, Morana and Sbrana

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

(2019) found that despite climate-led disasters have steadily increased from year 2000, the "multiple" (i.e. the return per unity of risk) of the CAT bonds has decreased.

Monasterolo and de Angelis analysed the US, EU and global stock market's reaction to the announcement of the Paris Agreement. They found that the overall systematic risk for the low-carbon indices decreases consistently, while stock markets' reaction is mild for most of carbon-intensive indices. Ramelli et al. (2018) and Wagner et al. (2018) analysed the stock market's reaction to the election of Trump as President of the United States, and the appointment of the climate skeptic Scott Pruitt as a head of the US Environmental Protection Agency, and found opposite results, i.e. that investors rewarded companies in high-emissions industries/companies demonstrating more responsible climate strategies.

With regard to sovereign bonds, Crifo et al. (2017) find that high country's Environmental Social Governance (ESG) ratings are associated with low borrowing costs (spread) for short-maturity sovereign bonds in advanced economics. In the contest of low-income countries, Kling et al. (2018) focus on the most climate vulnerable low-income countries (V20) exposed to climate physical risk occurred in the past. They find a slightly higher cost of debt for a few countries, but they also point out the caveats that apply, 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.

All these analyses, despite focusing on different types of financial contracts and climate risks analyse climate shocks that occurred in the past, and that could have represented a structural break in the series of prices and performance. In contrast, Battiston and Monasterolo (2019) developed the first approach to price *forward-looking* climate transition risks in the value of individual sovereign bonds, by including the characteristics of climate risks (i.e. uncertainty, non-linearity and endogeneity of risk) in financial valuation. They applied the model to the sovereign bonds of the OECD countries included in the Austrian National Bank (OeNB)'s non-monetary policy portfolio. They found that the (mis)alignment of an economy could already be reflected in the sovereign bonds' spread (i.e. the climate spread) and change the fiscal and financial risk position of a country.

Since financial investors take decisions based on what they can measure, and their decisions do influence (and are influenced by) the benchmark in their respective markets, assessing climate risks in financial contracts is crucial from an investors' risk management perspective, and for financial supervisors whose mandate is about preserving financial stability. To our knowledge, this article is the first study assessing climate-related financial risks stemming from insurance companies' exposures to sovereign bonds.

3. DATA SAMPLE

We utilized Quarterly Solvency II Reporting Template on List of Assets (SII QRT)[46] and Centralized Security Database (CSDB). Solo data of insurers from 31 countries in EU/EEA that reported Solvency II data at the end of 2018 are employed. Our dataset includes all insurers' investments into sovereign bonds (CIC code equal 1). This data is complemented by information on the characteristics of the bonds available from the CSDB. The final dataset contains 1576 insurance companies, 142 bond issuers and 10746 bonds. The total amount of the insurance government portfolio considered is 2.1 trillion EUR. The full description of the data set utilized in this study is provided in the table below.

46 S.06.02 template.

Table A1.1: List of variables utilized

Variable name	Description
Insurance identifier	Unique identifier of solo insurance company (SII QRT)
Home country	Country of authorization of the insurer (SII QRT)
ISIN code	ISIN conde of the sovereign bond (SII QRT)
Issuer's country	Country that issued the bond (SII QRT)
Duration	Residual duration of the bond (SII QRT)
Maturity	Maturity date of the bond (SII QRT)
Term	Difference in years between the date of bond's maturity and the date of bond issuance (SII QRT)
Price	Market value of the bond (SII QRT)
Nominal value	Nominal value of the bond (SII QRT)
Coupon	Coupon of the bond (CSDB)
Coupon type	Type of the bond's coupon (fix, zero coupon) (CSDB)
Coupon frequency	Coupon frequency of the bond (monthly, bi-monthly, quarterly, semi-annually, annually, zero coupon) (CSDB)

Note: All variables refer to 2018Q4.

4. METHODOLOGY

In this section, we introduce the concepts of climate physical and transition risks. Then, we define the climate policy shocks that we analyse in the context of a disorderly low-carbon transition. Finally, we present the CLIMAFIN tool that we apply to price forward-looking climate transition risk in the value of individual sovereign bonds (introducing the climate sovereign spread) under deep uncertainty, and to assess the largest gains/losses on investors' portfolios. CLIMAFIN includes climate scenarios adjusted financial pricing models (for equity holdings, sovereign and corporate bonds, and loans) and climate scenarios conditioned risk metrics (such as the Climate Spread and the Climate VaR). These allow us to embed forward-looking climate risk scenarios in the valuation of counterparty risk, in the probability of default of securities and in the largest losses on investors' portfolios (Battiston et al., 2019).

We opted for CLIMAFIN for two reasons. First, it is the first approach that combines forward-looking climate transition risk shocks and associated economic trajectories based on climate economic models (in this application, the LIMITS IAMs), which are the reference for the scientific community and the IPCC, with climate financial risk metrics and methods that are now a reference in both the academic and practitioners' community (Battiston et al., 2019). Second, CLIMAFIN provides a transparent and robust methodology for climate financial risk assessment under deep uncertainty. Importantly, this represents the first climate-financial risk assessment developed in collaboration between scientists of the climate economic community, climate financial risk experts and a financial regulatory institution with a financial stability mandate.

4.1. CLIMATE CHANGE AND FINANCIAL STABILITY: TRANSITION RISKS

Two main channels of risk transmissions from climate change to finance have been identified and analyzed so far, i.e. climate physical risks and climate transition risks. In our analysis we focus on *climate transition risk* because while climate physical risks are expected to be more visible in the mid to long-term period, triggering potentially irreversible socio-economic and environmental impacts (see IPCC 1.5°C 2018 Allen et al. 2018, Steffen et al. 2018), climate transition risks could happen sooner and be more financially relevant (V. de Gaulhau (2018))[47].

Climate transition risk refers to the economic and financial risk arising from a sudden revaluation of carbon-intensive and low-carbon assets and that cannot be fully anticipated by financial actors. This risk can be driven by (i) *Technological shocks* (e.g. the fast decrease of renewable energy production costs and fast increase in their performance, or the change in minimum technology standards); (ii) *Policy and regulatory shocks* (e.g. the disordered introduction of a global carbon tax IMF, 2019) or a change in prudential regulation such as the introduction of Green Supporting Factors (HLEG, 2018); (iii) the sudden changes in the *climate sentiments* of financial actors (Dunz et al., 2019), as a result of the expectations of market participants about the implementation of the climate policies.

Most important, climate risks differ from the type of risks that investors are used to consider in finance. In particular, the nature of climate risks introduces several conceptual and methodological challenges for traditional economic and financial models, which then need to consider (Monasterolo, 2019):

- *Non-linearity of impacts*. The probability of forward-looking climate shocks can't be inferred from historical data being non-linear and not normally distributed (Ackerman, 2017);
- *Forward-looking nature of risk***.** The impacts of climate change are on the time scale of two decades or longer[1]. 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.
- *Deep uncertainties* that characterize climate impacts and their costs, due to the nature of the earth system that 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 mean that the estimates of the costs and benefits of (in)action may vary substantially across climate scenarios with the assumptions on agents' utility function, future productivity growth rate, and intertemporal discount rate (Stern, 2008, Pyndick, 2013).
- *Endogeneity and circularity of climate risk*. The likelihood of achieving the global climate targets depends on the orderly introduction of climate policies, and their anticipation by financial actors in their investment decisions. However, climate policies' uncertainty affects investors' expectations on the financial risk deriving from the very same policies, and thus their investment decision. In turn, the lack of climate aligned investments makes it impossible to achieve the climate policy targets. This generates the possibility of multiple equilibria, a situation where a rational agent cannot identify a preferred investment strategy (Battiston and Monasterolo, 2018).

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47 https://www.bis.org/review/r180419b.htm

4.2. THE CLIMAFIN CLIMATE FINANCIAL RISK PRICING MODEL

4.2.1. Climate policy scenarios

We consider the climate policy scenarios developed by the International Scientific Community and reviewed by the IPCC. In particular, we select all the climate policy scenarios aligned to the 2°C target made available from the LIMITS project, which includes six IAMs. We use the LIMITS project database (Kriegler et al., 2013) to compute the trajectories of the shocks in the market shares for several variables, including the output of all the economic activities in primary and secondary energy (e.g. primary energy from fossil fuels, electricity produced by solar panels, etc.) conditioned to climate policies' introduction (i.e. a carbon tax). The two emissions concentration targets chosen under milder and tighter climate policy scenarios (i.e. 500 parts per million (ppm) and 450 ppm) refer to the stabilization concentration of CO2 at the end of century consistently with the 2°C aligned scenarios, and are associated to two different policy implementation scenarios, i.e. the

Reference Policy (RefPol) and the Strong Policy (StrPol) (IPCC, 2014). RefPol assumes a weak near-term target by 2020 with fragmented countries' action, while StrPol assumes a stringent near-term target by 2020 with fragmented countries' action, to achieve emissions reduction by 2050. The 500 and 450 ppm scenarios are associated to a probability of exceeding the 2°C target by 35-59% and 20-41% respectively (Menishausen et al., 2009). Thus, the choice of specific emissions concentration targets could be considered as a proxy for the stringency of the global emission cap imposed by potential climate treaty. 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 based on their energy technology (fossil/renewable).

4.2.2. Climate policy shocks

In the context of climate transition risks, climate policy shocks are defined as the transition from a business as usual scenario of no climate policy, to a policy scenario characterised by the introduction of a climate policy (e.g. a carbon tax, or a Green Supporting Factor). Climate policy shocks arise from a disorderly transition, i.e. when the introduction of climate-aligned policies is carried out at a schedule that is not predictable by investors. These, in turn, cannot fully anticipate (and price) it in their portfolios' risk management strategies (Battiston et al., 2017; NGSF, 2019). In the current scenario where governments have not coordinated yet to introduce stable climate policies, we might end up in a disorderly transition scenario (Battiston, 2019). The transition entails a jump from one equilibrium state of the economy (e.g. the current state) to another equilibrium state where the composition of the economy and the weight of the economic activities (carbon-intensive, low-carbon) could consistently change.

In a disorderly transition, assets price adjustments would directly or indirectly negatively impact the value of fossil fuels and related assets. The lack of investors' anticipation of the climate policy shock could have relevant and long-lasting consequences for the financial conditions of a private investor and of a sovereign, and eventually it would affect the achievement of the 2°C aligned climate mitigation scenarios. As several recent policy events show (e.g. the US withdrawal from Paris Agreement, the outcome of 2018 Italian elections), the assessment of the future policy shock could be incorrect even on average across market participants, and yet can have severe long-term effects on the financial conditions of a country (Battiston, 2019).

4.2.3. Investors' information set

Here we present the information set that a rational risk averse investor should use to assess financial risk under climate transition scenarios. We consider a risk averse investor that aims to assess the exposure of her portfolio to forward-looking climate transition risk. This information set can accommodate the presence of incomplete information and deep uncertainty (Keynes, 1973; Knight, 1921; Greenwald and Stiglitz, 1986). The information set covers a time-horizons that is relevant both for investment strategies and for the low-carbon transition from 2020 to 2050, and is composed of:

- **Climate policy scenarios** corresponding to Greenhouse Gases (GHG) emission reduction target across regions (B = Business-as-Usual), provided e.g. by the IPCC reports;
- The future **economic trajectories** for carbon-intensive and low-carbon activities, provided by climate economic models (e.g. IAMs);
- A set of forward-looking **Climate Policy Shock Scenarios** intended as a disorderly transition from B (Business as Usual) to P (a given climate policy scenario);
- A set of **Climate Policy Shocks** on the economic output of low-carbon/carbon-intensive activities, on their Gross Value Added (GVA) and on their contribution to the fiscal revenues of the sovereign. The policy shocks are conditioned to transition scenarios and, to a specific climate economic model.

4.2.4. Investors' risk management strategy

The investor's risk management strategy is based on the minimization of the worst-case losses of the portfolio under different forward-looking climate transition scenarios. The definition of the risk management strategy accounts for (i) the investor's specific risk aversion levels, (ii) the counterparty risk adjusted for climate policy shock scenarios (e.g. Probability of Default (PD)), (iii) metrics relevant for financial regulation (e.g. risk measures such as the Climate Spread and VaR). The Climate VaR Management Strategy can be written as:

$$\text{ClimVaRStr} = \min_{\text{Portfolio}}\{\max_{\text{Shock}}\{\text{VaR}(\text{Portfolio}, \text{Adj.PD} \mid \text{Policy Shock})\}\}$$

In this context, future asset prices are subject to shocks that depend on the issuer's future economic performance, the risk premia demanded by the market, as well as the implementation of the climate policy and the outcome of the energy transition of individual firms and countries. 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 carbon-intensive or low-carbon economic activities and firms. 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 firms and 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.

4.2.5. 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 Rev 2), which identify the main sectors that are relevant for climate transition risk (fossil-fuel, electricity (from fossil or renewable sources), energy-intensive, transportation (low/high-carbon), buildings), and were originally introduced in Battiston et al. (2017). As a difference from the NACE classification of economic sectors, CPRS Rev 2 capture the energy and electricity technology embedded in the economic activity (e.g. utility|electricity|wind, solar, gas). Firms that compose economic sectors *S* are considered as a portfolio of cash-flows. The classification of countries and regions affected by the climate shock is based on the LIMITS aggregation[48], see Kriegler et al. (2013).

4.2.6. Impact of climate policy shock on economic activities' GVA and profitability

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

In a disorderly transition, a climate policy shock affects the performance of issuers in sectors *S* via a change in economic activities' market share, cash flows and profitability, eventually affecting the 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. from Eurostat). Negative shocks result from the policy impact on the GVA of sectors based on carbon-intensive (i.e. fossil fuels) technologies, while positive shocks result from the impact on the GVA of sectors based on low-carbon (i.e. renewable energy) technologies.

We assume that a percentage shock on output to a percentage shock on GVA, u_j^{GVA},for each sector *j*,so that:

$$u_j^{GVA}(P) = \frac{GVA_j(P) - GVA_j(B)}{GVA_j(B)} = \sum_S u_{j,s}^{GVA}(P)\, w_{j,s}^{GVA}(B)$$

Where $u_{j,s}^{GVA}(P)$ is the shock on the GVA of sector *S* of the sovereign issuer *j;* $w_{j,s}^{GVA}(B)$ is the share of GVA of sector *S*. We then define the net fiscal assets related to sector *S*, $A_j(S)$,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 $A_j(S, P, M)$ as follows:

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

Where χ denotes the elasticity of sector *S* profitability with respect to the market share. While the policy shock could affect at the same time several sectors in the economy of the issuer *j*, here we consider the total net effect on the issuer's net fiscal assets as follows:

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

$$\frac{\Delta A_j(P,M)}{A_j} = \sum_s \left(\frac{\Delta A_j(S,P,M)}{A_j(S)} \frac{A_j(S)}{A_j}\right) = \sum_s \chi_s \, u_j(S,P,M) \frac{A_j(S)}{A_j}$$

The elasticity coefficient could be estimated empirically for the specific sectors of the sovereign issuers in the portfolio. However, in our application, the data to carry out this estimation was not available. Thus, for estimating the elasticity we consider a mild and adverse scenario with values equal to equal to 0.2 and 0.5, respectively (see also Battiston and Monasterolo, 2019). This allows us to provide an estimation of the magnitude of the shocks due to a given climate policy scenarios *P*, where the shock is transmitted to the value of the sovereign bond via the change in sectors' market share, GDP and fiscal assets.

4.2.7. Model for sovereign bonds' valuation

We consider a risky (defaultable) bond of a sovereign entity *j*, issued at t_0 with maturity *T*. The value of the sovereign bond at time *T*, with *R* being the Recovery Rate of the bond (i.e. the percentage of notional recovered upon default), and LGD Loss-Given-Default (i.e. the percentage loss) can be written as:

$$v_j(T) = \begin{cases} R_j = (1 - LGD_j) & if\ j\ defaults\ (with\ probability\ Q_j) \\ 1 & else\ (with\ probability\ 1 - Q_j) \end{cases}$$

The unitary price $P_j(t)$ of the sovereign bond at time t<T and t>t_0 follows the usual definition of discounted expected value at the maturity,

$$\Delta q_j(P) = q_j(P) - q_j(B) = \int_{\eta_{inf}}^{\theta_j(P)} \phi_{(\eta_j)} d\eta_j, \text{ with } \theta_j(P) = \theta_j(B) - \xi_j(P)$$

$$P_j = \exp(-r_f(T-t))\ E[v_j(T)] = \exp\left(-r_f(T-t)\right)\ (1 - Q\ LGD),$$

where r_f is the risk-free rate and the expectation is taken under the risk neutral measure. Moreover, the cumulative probability of default *Q*, is related to the annual probability of default as follows: $Q = 1 - (1 - q)^{(T-t)}$.The formula can be used to determine from the market price the value of the annual default probability q, called "q implied", for a given risk free rate and LGD. In the case of a multi-coupon bond, the formula gets more complicated since one has to sum over the expected value of the coupons but the logic remains the same. For each coupon *k*, the coupon amount is assumed to be paid only if *j* does not default before. The determination of the q implied requires then to solve numerically a polynomial equation.

4.2.8. Sovereign default conditions

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. Differently from Gray et al. (2007), we do not consider whether debt is issued in local or foreign currency, nor the exchange rate risk.

We can define the sovereign's net fiscal assets at the present time of the valuation and at the maturity respectively as $A_j(t)$ and $A_j(T)$,and the liabilities at the maturity as $L_j(T)$.Thus, the sovereign default conditions read as:

$$A_j(T) = A_j(t)\ (1+\eta_j(T)) < L_j(T)$$

We add a climate policy shock ξ_j on *j*'s net fiscal assets (as a "jump" up or down), assuming that the idiosyncratic shock η_j and policy shock ξ_j are independent. The new sovereign default condition reads as:

$$A_j(T) = A_j(t)\ (1+\eta_j(T) + \xi_j(P)) < L_j(T) \Leftrightarrow \eta_j(T) < \theta_j(P)$$
$$= L_j(T)/A_j(t) - 1 - \xi_j(T, P)$$

where $\theta_j(P)$ is the default threshold under scenario *P*, $\xi_j(P)$ is the climate policy shock from *B* to *P* (can be positive or negative) that shifts the idiosyncratic shock η_j, with $\xi_j(P)$>1, possibly correlated across *j*.

4.2.9. Sovereign default probability

We can define the Probability of Default (PD) $q_j(P)$ of issuer *j* under Climate Policy Scenario *P as:*

$$q_j(P) = \mathcal{P}\ (\eta_j < \theta_j(P)) = \int_{\eta_{inf}}^{\theta_j(P)} \phi_{(P)}(\eta_j) d\eta_j$$

where $\phi_{(P)}(\eta_j)$ is the probability distribution of idiosyncratic shock η_j, η_{inf} is the lower bound of distribution support.

In principle, frequent small productivity shocks across time and firms occur in a similar way, with or without the climate policy shock. We introduce now a proposition of the PD adjustment Δq conditioned to the climate policy shock, which shifts the probability distribution of the small productivity shocks and thus the default probability of issuer *j*:

$$\Delta q_j(P) = q_j(P) - q_j(B) = \int_{\eta_{inf}}^{\theta_j(P)} \phi_{(\eta_j)} d\eta_j, \text{ with } \theta_j(P) = \theta_j(B) - \xi_j(P)$$

Thus, assuming that the climate policy shock on fiscal asset is proportional to shock on GVA of low-carbon and carbon-intensive sectors i.e. $\xi_j = \chi_j u_{j,s}^{GVA}$ (*P*), with elasticity the adjustment $\Delta q_j(P)$, the default probability of sovereign *j* under Climate Policy Shock Scenario:

- Increases with GVA shock magnitude $|u_{j,s}^{GVA}(P)|$ if $u_{j,s}^{GVA}(P)<0$, and decreases vice versa;

Is proportional to the GVA shocks on the CPRS (in the limit of small Climate Policy Shocks).

5. EMPIRICAL RESULTS

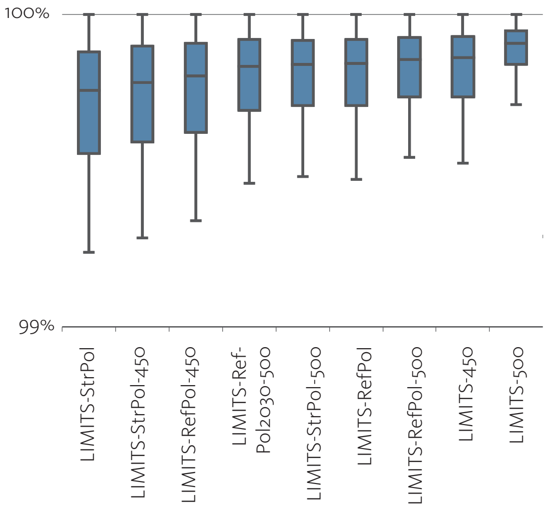
Overall, we consider the combination of two market conditions scenarios with climate policy scenarios described in Section 4. The market condition scenarios are reflected in the different values of loss-given-default LGD and elasticity.In the mild scenario, LGD = 0.2 and = 0.2. In the adverse scenario, LGD = 0.4 and = 0.5.

For each scenario combination and IAM, we compute the shock on the value of each bond in the holdings' dataset. The description of the scenarios considered in this exercise are provided in the Appendix. We then compute the resulting aggregate shocks on the value of the portfolio of each European insurance company ("solo"). We define as *portfolio impact* of the climate policy shock the ratio of the value of the portfolio after the shock over the initial value before the shock. In a series of boxplots, we study the distribution of the values of the portfolio impact of climate policy shocks under varying levels of aggregation. The difference between the median impact and 100% is considered as the *median shock* on the portfolio values.

Notice that three dimensions drive the magnitude of portfolio impact. First, for each sovereign bond negative shocks (e.g. on primary energy fossil sector) can be possibly compensated by positive shocks (e.g. on secondary energy electricity based on renewable sources). Second, in a portfolio of sovereign bonds issued by several countries, negative aggregate shocks from a less climate-aligned sovereign can be possibly compensated by positive shocks from another more climate-aligned sovereign (see also Appendix Table A1.3). Third, in some of the figures the results from several models or several scenarios are pooled together in one distribution. These three dimensions concur to limit the magnitude of the median value of the portfolio impact in the following charts. Further, recall that in this application of the CLIMAFIN framework, we do not consider the macro-economic reverberations of a shock on a given sector. Therefore, the results are to be considered as conservative.

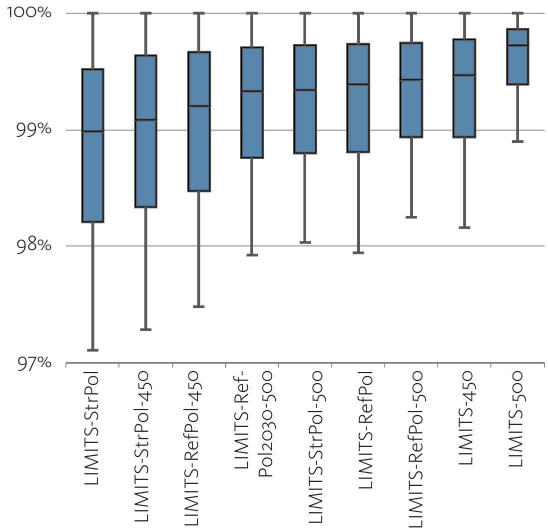
Chart A1.1-2 show the box plots of the portfolio impact distribution across insurance holders and IAMs, for selected climate policy scenarios. Chart A1.1 and A1.2 refer, respectively, to the mild and adverse scenario on market conditions. In the mild scenario, the first quartile of the distribution varies between 99.6% and 99.8%. In the adverse scenario, the same quantity varies between 98.2% and 99.4%. The median shock in the adverse scenario is about 3 times larger than in the mild scenario.

Figure A1.1: Distribution of impact on sovereign holdings of European insurers across climate policy shock scenarios, under the ***mild*** scenario on market conditions.



Source: EIOPA and own calculations

Figure A1.2: Distribution of impact on sovereign holdings of European insurers across climate policy shock scenarios, under the ***adverse*** scenario on market conditions.

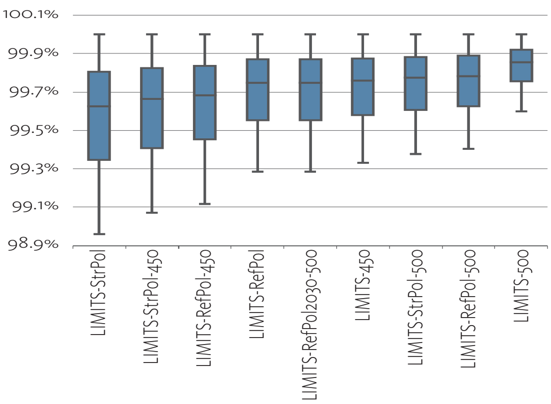


Source: EIOPA and own calculations

Note: Y-axis corresponds to the percentage of the original value of government portfolios (e.g. 100% expresses 0% impact, 97% corresponds to drop of 3%). The description of scenarios is provided in Appendix.

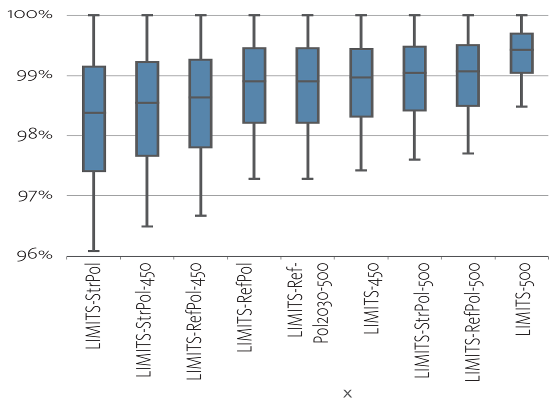
Chart A1.3-4 show the box plots of the portfolio impact distribution across holders, estimated by the model MESSAGE (Krey et al. 2016; Fricko et al. 2017), for selected climate policy scenarios. Chart A1.3 and A1.4 refer, respectively, to the mild and adverse scenario on market conditions. In the mild scenario, the first quartile of the distribution varies between 99.3% and 99.8%. In the adverse scenario, the same quantity varies between 97.4% and 99.0%. The median shock in the adverse scenario is again about three times larger than in the mild scenario.

Figure A1.3: Distribution of impact on sovereign holdings of European insurers estimated by the model MESSAGE across climate policy shock scenarios, under the ***mild*** scenario on market conditions.



Source: EIOPA and own calculations

Figure A1.4: Distribution of impact on sovereign holdings of European insurers estimated by the model MESSAGE across climate policy shock scenarios, under the ***adverse*** scenario on market conditions.

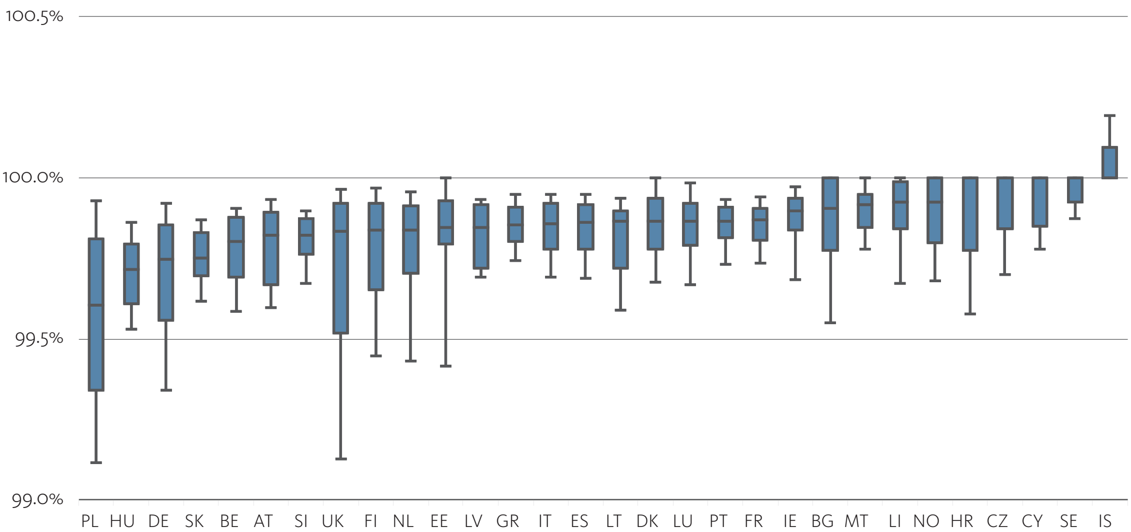


Source: EIOPA and own calculations

Note: Y-axis corresponds to the percentage of the original value of government portfolios (e.g. 100% expresses 0% impact, 97% corresponds to drop of 3%). The description of scenarios is provided in Appendix.

Chart A1.5-6 shows the box plots of the portfolio impact distribution across holders, conditioned to the country of the insurance holder, for a given selected climate policy scenario, and estimated across all the models in the LIMITS database (Kriegler et al. 2013). Chart A1.5 refers to the climate policy scenario RefPol500 and the mild market condition scenario. Chart A1.6 refers to the climate policy scenario StrPol450 and the adverse market condition scenario. In the mild scenario, the first quartile of the distribution varies between 99.3% and 100.0%. In the adverse scenario, thefirst quartile varies between 96.2% and 99.5%. The median shock in the adverse scenario is about 5 times larger than in the mild scenario. Note that we have excluded countries for which the number of observations did not allow to draw the box plot (i.e. Romania in A1.5, Romania and Iceland in A1.6).

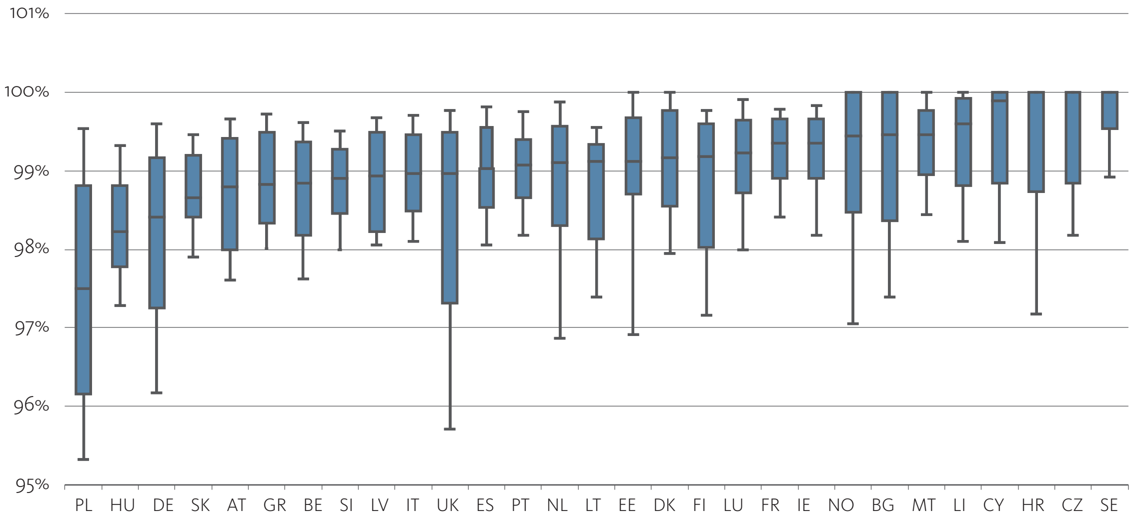
Figure A1.5: Distribution of impact on sovereign holdings of European insurers conditioned to the country of the holder, across climate policy shock scenarios and under the ***mild*** scenario on market conditions.



Source: EIOPA and own calculations

Note: Y-axis corresponds to the percentage of the original value of government portfolios (e.g. 100% expresses 0% impact, 97% corresponds to drop of 3%). The description of the scenarios is provided in Appendix.

Figure A1.6: Distribution of impact on sovereign holdings of European insurers conditioned to the country of the holder, across climate policy shock scenarios and under the ***adverse*** scenario on market conditions.



Source: EIOPA and own calculations
Note: Y-axis corresponds to the percentage of the original value of government portfolios (e.g. 100% expresses 0% impact, 97% corresponds to drop of 3%). The description of the scenarios is provided in Appendix.

The results of this analysis should be considered as conservative for the following reasons. First, since global GHG emissions are still increasing (WMO 2019) and countries are not aligning their policies to their climate pledges, stricter climate policies might be introduced. Second, the IAMs' policy scenarios that we considered were defined before the Paris Agreement. Thus, tighter policy scenarios are likely to be needed to achieve the 2°C target. Further, it must be noticed that the energy technology shocks (both on fossil and renewable energy sources) vary considerably across the IAMs used, for the same regions and countries considered. Finally, we should consider investors' sentiments, i.e. the expectations about changes in (even few decimal points) in GVA and GDP growth could impact sovereign bonds' yields.

6. CONCLUSION

In this analysis, we have developed the first climate transition risk assessment of the sovereign bonds' portfolios of solo insurance companies in Europe under deep uncertainty. This is the result of the first collaboration between, climate economics modellers, climate financial risk scholars and researchers from a public authority with a mandate to contribute to financial stability. We opted for the CLIMAFIN framework by Battiston et al. (2019) because it is the first and transparent approach that combines 1) forward-looking climate transition risk shocks obtained from climate economic models that are the reference for scientific community and the IPCC (in this context, the LIMITS IAMs) with; 2) climate financial risk metrics and methods that are now a reference in both the academic and practitioners' community (Battiston et al., 2017). In particular, the CLIMAFIN approach allows to embed forward-looking climate transition risk scenarios (i.e. a disorderly introduction of climate policies that cannot be fully anticipated and priced in by insurers) in the valuation of counterparty risk, in the probability of default of individual sovereign bonds and largest losses on investors' portfolios (Battiston et al., 2019).

In this application, we have considered a simple financial pricing model for zero and multi-coupon sovereign bonds adjusted for climate policy shock scenarios. This allows to compute an adjusted value of bonds' portfolios in order to assess how future climate transition risk could affect the probability of default of individual sovereign bonds, the financial solvability of the sovereign and the performance of European insurers who are exposed to those bonds. The analysis uses the solo data of insurers from 31 countries in EU/EEA that reported Solvency II data at the end of 2018, including all insurers' investments into sovereign bonds, complemented by information on the characteristics of the bonds available from the CSDB.

Our results show that the potential impact of a disorderly low carbon transition on insurers portfolios of sovereign bonds is moderate in terms of its magnitude. However, it is non-negligible in several feasible scenarios. Overall, it emerges that the climate policy transition path chosen, and the role of fossil fuels and renewable energy technologies in the sovereign's GVA and fiscal revenues, can considerably affect the fiscal and financial risk position of a country, via the change in the probability of default (PD) and in the value of the sovereign bonds and the Climate Spread. In general, countries that have already started to align their economy to the low-carbon transition (and thus where renewable energy technologies play a larger role on its GVA and fiscal revenues) face a decrease in the PD and in the Climate Spread, and thus better refinancing conditions. In contrast, countries whose GVA is carbon intensive would face an increase in the PD and in the Climate Spread.

This, in turn, could have relevant implications for the financial risk profile of the insurers who own sovereign bonds of countries that are misaligned to the low-carbon transition and the climate targets. Thus, it would be in the interest of insurers' supervisors to extend this climate financial risk pricing exercise (ideally in a climate stress-test exercise, see e.g. Battiston et al., 2017) for financial risk monitoring and assessment purposes.

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APPENDIX

CLIMATE POLICIES SCENARIOS LIMITS.

In this exercise we consider the scenarios elaborated by the international scientific consortium LIMITS. This is a database of economic trajectories that are consistent with 10 climate transition scenarios. The main features of climate mitigation are the following:

- The level of ambition in emission reduction in the near-term (2020):
  - reference policy 'weak' corresponds to unconditional Copenhagen Pledges; more 'stringent' based on conditional Copenhagen Pledges.
- The level of ambition in emission reduction in the long-term (2100):
  - either no target or concentrations targets of 450 and 500 ppm CO2-eq, corresponding to high chances of achieving 2°C
- The level of international cooperation until 2020 and 2030:
  - no cooperation, fragmented action, coordinated action.

Table A1.2: LIMITS scenarios' characteristics.

Scenario class	Scenario name	Scenario type	Level of ambition (near term)	Level of ambition (long term)	Level of international cooperation
No policy	Base	Baseline	None	N/A	None
Fragmented action	RefPol	Reference	Weak	2100	None
	StrPol	Reference	Stringent	2100	None
Immediate action	450	Benchmark	None	N/A	450 ppm
	500	Benchmark	None	N/A	500 ppm
Delayed Policy	RefPol-450	Climate Policy	Weak	2020	450 ppm
Delayed Policy	StrPol-450	Climate Policy	Stringent	2020	500 ppm
Delayed Policy	RefPol-500	Climate Policy	Weak	2020	500 ppm
Delayed Policy	StrPol-500	Climate Policy	Stringent	2020	500 ppm
Delayed Action	RefPol2030-500	Climate Policy	Weak	2030	501 ppm

Source: Table based on: E. Kriegler, M. Tavoni, T. Aboumahboub, G. Luderer, K. Calvin, G. De Maere, V. Krey, K. Riahi, H. Rosler, M. Schaeffer, D. van Vuuren (2013): Climate Change Economics 4(4), doi: 10.1142/S2010007813400083.

We consider the trajectories computed under 6 Integrated Assessment Models (AIM-Enduse, GCAM, IMAGE, MESSAGE, REMIND, and WITCH). More information is available at: https://tntcat.iiasa.ac.at/LIMITSDB/dsd?Action=htmlpage&page=about#tutorial

CLIMATE POLICIES SCENARIO LIMITS REDPOL-450 MILD COMPUTED WITH THE IAM MESSAGE

The following table provides simple average of results of shock for the scenario LIMITS RedPol-450 mild computed with the IAM MESSAGE aggregated by bond issuers and their residual maturities. The sovereigns that were not sufficiently represented across different residual maturities were excluded from the table. As sovereign bonds that are held by insurers in their investment portfolios could have different parameters, the obtained results were smoothed out using estimated linear trends. In this way the results could be generated even for residual maturities that were not available in our data sample. The following table could be used as an illustrative example how to integrate forward-looking climate transition in a bottom up insurance stress test. The climate shocks could be then combined with other shocks, e.g. market shocks prescribed in the given stress test scenario.

Table A1.3: Average impact of scenario LIMITS RedPol-450 mild computed by IAM MESSAGE for different sovereigns and residual maturities

	1	2	3	4	5	6	7	8	9	10	15	20
Austria	-0.31%	-0.33%	-0.35%	-0.37%	-0.38%	-0.40%	-0.42%	-0.44%	-0.46%	-0.48%	-0.57%	-0.66%
Belgium	-0.24%	-0.27%	-0.29%	-0.31%	-0.34%	-0.36%	-0.38%	-0.41%	-0.43%	-0.45%	-0.57%	-0.68%
Denmark	-0.07%	-0.10%	-0.13%	-0.16%	-0.19%	-0.22%	-0.25%	-0.29%	-0.32%	-0.35%	-0.50%	-0.65%
Finland	-0.07%	-0.11%	-0.15%	-0.19%	-0.23%	-0.27%	-0.31%	-0.35%	-0.39%	-0.42%	-0.62%	-0.82%
France	-0.32%	-0.34%	-0.37%	-0.39%	-0.42%	-0.45%	-0.47%	-0.50%	-0.52%	-0.55%	-0.67%	-0.80%
Germany	-0.12%	-0.19%	-0.25%	-0.31%	-0.38%	-0.44%	-0.50%	-0.56%	-0.63%	-0.69%	-1.00%	-1.32%
Greece	-0.26%	-0.27%	-0.27%	-0.28%	-0.28%	-0.29%	-0.30%	-0.30%	-0.31%	-0.31%	-0.34%	-0.37%
Iceland	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Ireland	-0.01%	-0.07%	-0.13%	-0.18%	-0.24%	-0.30%	-0.36%	-0.42%	-0.48%	-0.54%	-0.83%	-1.12%
Italy	-0.22%	-0.2.3%	-0.25%	-0.26%	-0.27%	-0.29%	-0.30%	-0.31%	-0.33%	-0.34%	-0.40%	-0.47%
Luxembourg	-0.02%	-0.04%	-0.07%	-0.09%	-0.12%	-0.14%	-0.16%	-0.19%	-0.21%	-0.24%	-0.36%	-0.48%
Netherlands	-0.10%	-0.20%	-0.30%	-0.40%	-0.50%	-0.60%	-0.70%	-0.80%	-0.90%	-1.00%	-1.49%	-1.99%
Norway	-0.01%	-0.01%	-0.02%	-0.02%	-0.02%	-0.03%	-0.03%	-0.04%	-0.04%	-0.04%	-0.06%	-0.08%
Poland	-0.74%	-0.73%	-0.72%	-0.71%	-0.70%	-0.69%	-0.68%	-0.67%	-0.66%	-0.65%	-0.60%	-0.54%
Spain	-0.18%	-0.21%	-0.25%	-0.28%	-0.32%	-0.35%	-0.39%	-0.42%	-0.46%	-0.49%	-0.67%	-0.84%
Sweden	-0.02%	-0.02%	-0.02%	-0.01%	-0.01%	-0.01%	-0.01%	0.00%	0.00%	-0.01%	0.00%	0.01%
United Kingdom	-0.33%	-0.28%	-0.23%	-0.18%	-0.12%	-0.40%	-0.44%	-0.47%	-0.50%	-0.53%	-0.69%	-0.85%
Switzerland	-0.24%	-0.28%	-0.31%	-0.34%	-0.37%	-0.07%	-0.02%	0.00%	0.00%	0.14%	0.40%	0.66%
United States	-0.13%	-0.13%	-0.14%	-0.14%	-0.15%	-0.16%	-0.16%	-0.17%	-0.18%	-0.18%	-0.22%	-0.25%

Source: EIOPA and own calculations
Note: The columns represent residual maturities. The obtained results were smoothed out cross residual maturities using estimated linear trends.