The skin-in-the-game bond: a novel sustainable capital instrument

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Abstract

We introduce a novel sustainable capital instrument: the skin-in-the-game bond. With features inspired by contingent convertibles (CoCos), this bond is an alternative for the green, social, sustainability and sustainability-linked bonds available on the market. A skin-in-the-game bond is linked to the performance of a benchmark that relates to the broad concept of sustainability in at least one of its pillars, being the environment (E), society (S) or corporate governance (G). When the benchmark hits a preset trigger level, (part of) the bond's face value is withheld and directed into a government-controlled fund by the issuer. The skin-in-the-game bond offers a higher yield to investors than a standard corporate bond, in order to compensate for the risk of losing out on (part of) the investment. Both issuer and investor have skin-in-the-game; the embedded financial penalty incentivizes the preservation of a favorable benchmark value. In this work, we elaborate on the general concept of a skin-in-the-game bond, as well as on a tailored valuation model, illustrated by two examples: the ESG and nuclear skin-in-the-game bonds.

Keywords: contingent convertible bond, skin-in-the-game bond, sustainable finance, ESG, sustainable capital instrument

1 Introduction

Topics related to sustainable investing rise up more rapidly than ever on the public and scientific agenda. According to the European Commission's action plan for financing sustainable growth, sustainable investing refers to the process of taking due account of environmental (E), but also social (S) and corporate governance (G) considerations in investment decision-making (European Commission, 2018). Banks and asset management firms, as well as large institutional investors such as (re)insurers and pension funds have a key role to play when reorienting

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finance towards such investments. Lessons learned from the 2008 financial crisis are driving forces in this transition. Skin-in-the-game (Taleb, 2018), transparency, regulation and proper risk management tools are crucial, since the lack of these paved the way to the last crisis.

Within the toolkit of state-of-the-art sustainable investments, green, social and sustainability bonds play a pioneering role. A green bond is a debt instrument issued to exclusively finance projects or business activities with environmental benefits, while social bonds expand the scope of green bonds to projects with positive social outcomes. The hybrid of green and social bonds, sustainability bonds, finance projects with both social and environmental objectives (Park, 2019). The ever-growing popularity of these sustainable products raises awareness about key challenges that can undermine the evolution of the bonds as credible market products (CBI, 2021b). There is an emerging need to standardize the sustainable debt market (Deschryver and de Mariz, 2020; Tuhkanen and Vulturius, 2020), despite the existence of several non-binding frameworks such as the Principles of the International Capital Markets Association (ICMA, 2021), the certification standard of the Climate Bonds Initiative (CBI, 2021a) and the Green Bond Standard of the EU Technical Expert Group (EU TEG, 2020). The absence of universally accepted principles about what constitutes 'green' and no obligations to report on the use of allocated proceeds after issuance lead to so-called 'greenwashing'. Greenwashing refers to the deceptive promotion of the perception that an organization's products, aims or policies are environmentally friendly (Doran and Tanner, 2019). Moreover, due to the lack of a punishment if the bond's issuer fails to deliver the promised results, the issuer has no skin-in-the-game, and moral hazard is created. Moral hazard is generally described as the situation in which negative consequences of an act are not all borne by the risk-taker himself but are also paid for by society.

History has shown us more than once the dangers and severe consequences of situations where moral hazard is present. As an example, at the end of April, 2010, the Deepwater Horizon oil rig operated by BP killed 11 workers and sent millions of barrels of oil into the Gulf of Mexico (Friedman and Friedman, 2014). A clear case of moral hazard was created in the years leading up to the oil spill; the 1990 US Oil Pollution Act capped a firms' liability for economic damages from oil spills at 75 million USD, while drilling in the deepest parts of the Gulf led to billion dollar rewards. With ultimately more than 28 billion USD on damage claims and clean-up costs, the excess losses borne by U.S. taxpayers were massive (Wood, 2016).

The limited liability principle in today's economy thus constitutes a powerful source of moral hazard (Djelic and Bothello, 2013). Once a firm is allowed to exist as a limited liability entity, it accesses the option to put excess losses back to the economy for free. Most of the time, these excess losses are quite moderate. However, so-called tail events may occur with very low probability, while having severe impact. That impact should not be underestimated, as the Deepwater Horizon example illustrates. Another tail event that shares a lot of similarities with the oil spill crisis, and is of particular interest to us, is the 2008 financial crisis. Due to conflict of interests and excessive risk-taking, we almost witnessed a breakdown of our financial system in 2008 (Crotty, 2009). During and after the crisis, a tremendous amount of taxpayers' money was spent or put at risk to keep (too big to fail) financial institutions alive.

In the wake of the 2008 financial crisis, regulators tried to wipe out excessive risk-taking and moral hazard risk in the banking sector. In order to avoid further bail-outs financed with taxpayers' money, the Basel committee proposed the Basel III framework to enforce higher capital levels and additional loss absorbing buffers (Basel Committee on Banking Supervision, 2010). In the new banking regulations, contingent convertible (CoCo) bonds play an important role as high yield instruments with loss-absorbing capacity (De Spiegeleer et al., 2014). A CoCo bond converts into shares or suffers a write-down of the face value upon the appearance of a trigger event, often characterized by a low value of the bank's CET1 ratio. This low CET1 ratio indicates a distressed situation for the financial institution, a said tail event.

Building upon the initial ideas of De Spiegeleer and Schoutens (2019), this contribution transfers the concept of a CoCo bond into a new capital instrument, focused on delivering upon E, S and G commitments: a skin-in-the-game bond. This instrument goes beyond the traditional green, social or sustainability bonds by embedding a financial penalty that connects sustainability promises with actual performance. If the issuer hits a preset trigger condition, investors miss out on a coupon payment or even forgo the complete face value of the bond. The issuer is obliged to direct the withheld part of this face value into a government-controlled fund. As such, the issuing company is not exempt from payment and society may be compensated for the damage caused. The skin-in-the-game bond is built on the principle that both parties, issuer and investor, should have skin-in-the-game and suffer if sustainability promises are not delivered. Moreover, transparency is enhanced; in order to monitor the trigger, the issuer is forced to publish reliable information on its sustainability-related commitments.

On the one hand, the skin-in-the-game bond compares to what is called a sustainability-linked bond (SLB), of which the first was launched in September 2019 by the Italian energy company Enel (Enel, 2021). The structural characteristics of this type of bond are adjusted depending on the achievement of predefined sustainable objectives. For most issued SLBs, failing to reach the sustainability performance targets (SPTs), measured through predefined key performance indicators (KPIs), results in a coupon step-up by a number of bps (ICMA, 2020). That way, the issuer creates an incentive to reach its sustainability goals. However, investing in these type of SLBs means speculating on *not* meeting sustainable targets, and a problematic revised incentive for the investor is created. Truly green investors should not be willing to earn money to the detriment of any sustainable objectives. Although the creature of SLBs is a step in the right direction, our proposed skin-in-the-game bond goes one step further, and aligns a company's incentives with a true sustainable investor's interests.

On the other hand, with the involvement of the third party, the external fund, the skin-in-the-game bond shares some characteristics with catastrophe (cat) bonds or insurance-linked securities in general. The distinguishing feature of a cat bond is that the principal is used to cover the costs of a related catastrophe, when it occurs (Burnecki et al., 2011). While some of the catastrophes for these bonds are not necessarily related to E, S or G commitments of a company (hurricanes, earthquakes, etc.), others are, for example cat bonds for offshore oil spill liability. Catastrophe bonds are usually sold by (re)insurance companies and governments who use them to mitigate their exposure to risk. In contrast, the skin-in-the-game bond aims for a wider applicability, by being open to issuance by companies in any sector. Also, that way, costs are not only covered by investor's money, via the principal, but are also partially paid for by the company who causes the costs, via the coupons. A catastrophe bond serves as a (re)insurance product, a risk transfer solution, whereas the skin-in-the-game bond has the primary purpose of enforcing skin-in-the-game and by that avoiding a catastrophe.

This paper is organized as follows. Section 2 investigates the design of several skin-in-the-game bonds, with a focus on versions with a continuous or counting benchmark. Section 3 outlines a custom-made valuation model inspired by the credit derivatives model for CoCo bonds (De Spiegeleer and Schoutens, 2012). Sections 4 and 5 focus on two illustrative examples; the ESG and nuclear skin-in-the-game bonds. Section 6 concludes.

2 The design of a skin-in-the-game bond

The design of the skin-in-the-game bond finds inspiration in the construction of contingent convertible bonds, established in the aftermath of the 2008 financial crisis. While the CoCo bond is mainly created for the banking sector, the skin-in-the-game bond can be tailored to the specific characteristics of a company in any sector.

2.1 The CoCo bond

Contingent convertible bonds are hybrid securities issued by financial institutions as a direct result of the more stringent capital requirements set out in the Basel III accord (Basel Committee on Banking Supervision, 2010). The standard corporate bond serves as a base for the instrument; investors receive a stream of fixed coupon payments together with a redemption of the notional investment at maturity. However, if a bank enters into a life-threatening situation due to unexpected losses, a so-called tail event, and its capital level consequently falls below a low threshold, investors will witness a complete or partial loss of their investment. This constitutes the loss-absorbing capacity of a CoCo bond; investors automatically bear part of the losses of the financial institution in distressed situations. As such, the institution can remain in a stable financial situation and the cost of a government bail-out is reduced.

The CoCo bond is a non-standardized instrument. Dependent on the type of the bond, the trigger event will cause a (full or partial) write-down of the bond's face value or a conversion of the bond into shares. The bottom line in any of these situations is similar: the conversion or write-down is not voluntary, and investors will suffer an important loss if the trigger event occurs. As a consequence, the proposed yield on the investment has to be high enough in order to get investors to underwrite the additional risk. Moreover, the yield level of the bond acts as an indicator for the healthiness of the issuing institution. The more risk the institution takes, the higher the yield the market will charge. This way, the CoCo bond's mechanism reduces moral hazard; it provides an incentive for the issuer to control risks, since excessive risk-taking will immediately lead to a higher cost of capital.

The trigger mechanism of a CoCo bond can be activated in different ways. First, the healthiness of a bank's balance sheet is measured using an accounting or capital ratio. The ratio most often used in practice is the Common Equity Tier 1 (CET1) ratio. A life-threatening situation for the institution is then defined by the ratio falling below a preset trigger level. Second, a regulatory trigger allows for the national regulator of the bank to decide on the financial situation of the institution. This way, the CoCo bond can be triggered at any point in time if forced by the regulator, to prevent the bank's insolvency.

CoCo bonds thus offer investors a higher yield in return for loss-absorbing capacity. The instrument's mechanism enforces skin-in-the-game for both issuer and investor; it is in the best interest of the two parties to stabilize the financial health of the institution. The issuer lowers its cost of capital, while the investor will not lose out on (part of) the investment. A more extensive discussion on contingent convertibles can be found in De Spiegeleer et al. (2014) and De Spiegeleer et al. (2018), including an in-depth analysis of the design of CoCo bonds and their application in light of the Basel III regulatory framework, as well as the development of tailored valuation methods for different types of CoCos.

2.2 The skin-in-the-game bond

While the focus of CoCo bonds is on the financial health of banks, awareness grows globally about the achievements and intentions of companies in any sector regarding environmental, social and corporate governance topics. Therefore, we see potential in financial instruments with an embedded financial penalty for all parties involved, linked to at least one E, S or G related commitment. The general aim of the product is to enforce skin-in-the-game, which fights moral hazard risk. When the instrument is issued by companies active in areas exposed to severe tail risk, the product may reduce the exposure of taxpayers, and in general society as a whole, to potential losses.

2.2.1 General structure

The skin-in-the-game bond functions as a standard corporate bond when no trigger is hit; a fixed coupon is paid at regular points in time (e.g. annually) to the investor and the notional value is redeemed at maturity. However, when the trigger mechanism of the bond is activated, the investor will suffer a loss on his investment, the size of which depends on the characteristics of the bond. Upon this trigger event, the skin-in-the-game bond differs from the CoCo bond in the direct involvement of a third party: a (national) regulator or government controlling a fund. The regulatory fund is then used to collect the withheld part of the face value. This way, the bond's design creates an additional incentive for the issuer to deliver sustainability promises; the issuer is not exempt from payment, whereas this is the case for a CoCo bond's issuer.

Like the CoCo bond, the skin-in-the-game bond is a non-standardized instrument where the benchmark, trigger type and trigger penalty can be tailored to the issuance. In what follows, we discuss these different components.

Benchmark and trigger type The skin-in-the-game bond is a versatile product and there is no unique benchmark that can be utilized. For the skin-in-the-game bond to be a sustainable capital instrument, the benchmark must be related to sustainability in at least one of its pillars, being the environment, society or corporate governance. Once a decision is made on the benchmark, a trigger level is fixed. This level is chosen in such a way that the benchmark breaching the trigger level indicates a situation of high (tail) risk, with consequences harmful to the environment and society.

Inspired by the selection criteria of KPIs for sustainability-linked bonds, as reported in ICMA (2020), an ideal benchmark is, in general, unambiguous, objective, easy to measure and monitor, relevant and ambitious. Unambiguity is needed as a trigger event has concrete, and often severe, financial consequences for all parties involved. In order to avoid conflict of interest, it must be possible to assess the value of the benchmark in an objective manner. An easy to measure and monitor benchmark will allow the bond to trigger timely and conduces effective risk assessment. Also, the benchmark should be relevant and related to the issuer's core business. Lastly, the trigger level may not be fixed such that a favorable benchmark value is too easy to achieve, which gives a false perception about a company's performance.

We distinguish between two types of benchmarks, both clarified with an example in Section 4 and 5.

- *Continuous benchmark.* A first, so-called continuous benchmark is based on the quantification of a relevant parameter or rating, which, in principle, can be monitored continuously, e.g. the greenhouse gas (GHG) emission or ESG rating of a company. A GHG skin-in-the-game bond triggers when a company fails to meet a preset (low) target level of GHG emission, whereas an ESG skin-in-the-game bond triggers when a company's ESG score falls below the trigger level (see Section 4).

- *Counting benchmark.* A second benchmark is based on the occurrence of a number of events of interest in relation to the total exposure, as modeled by a counting process, i.e. a so-called counting benchmark. Examples are the number of nuclear incidents occurring within a nuclear power plant with respect to the total net capacity of the plant (see Section 5) or the number of burn-outs within a company with respect to the total number of employees. Both skin-in-the-game bonds trigger when the event rate is too high, namely above a fixed trigger level.

Trigger penalty Inspired by the trigger penalties of a CoCo bond, the activation of a skin-in-the-game bond's trigger clause will affect the payout of future coupons and in some cases also the redemption of the notional. For a **continuous benchmark**, we envisage the following trigger penalties, analogous to the different CoCo bonds described in De Spiegeleer et al. (2014).

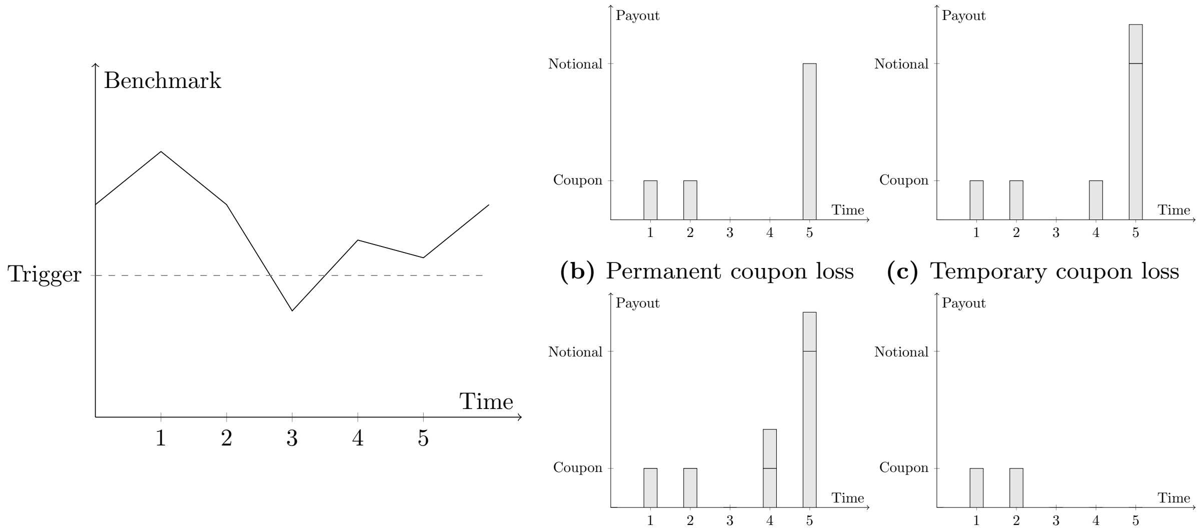
- *Permanent coupon loss.* All future coupons are canceled upon a trigger event. The trigger event is a non-cumulative coupon cancellation clause; once a coupon is not paid out, it is impossible to recuperate this cash-flow in a later stage. Regardless of whether a trigger event occurs, the notional amount is paid to the investor at maturity.
- *Temporary coupon loss.* Coupons are not paid out as long as the trigger clause is activated. Once the trigger condition is no longer met, coupons are paid out as planned to the investor. In any situation, the notional amount is redeemed at maturity.
- *Coupon withholding.* As long as the trigger condition is met, coupons are withheld. Once the trigger is no longer activated at a payment date, withheld coupons, together with the normal coupon, are paid out. If the trigger condition still holds on the maturity date, only the notional is redeemed.
- *Full write-down.* Once the trigger clause is activated, all outstanding coupons as well as the redemption of the notional are canceled.

As an illustration, the evolution of a continuous benchmark is pictured in Figure 1a. The payout structures of corresponding skin-in-the-game bonds with a maturity of five years, annual coupon payments and a varying trigger penalty are shown in Figure 1b to 1e.

In case of a **counting benchmark**, we go one step further by not only taking into account the yearly number of events, but also the cumulative number of events, over the full duration of the bond. We therefore envisage the following generic skin-in-the-game bond structure, illustrated in Figure 2.

Assume that the yearly number of arrivals of an event of interest, in relation to a particular exposure, can be modeled by a counting process. The event of interest is specified in such a way that the higher the number of arrivals, the stronger the negative effect on at least one of the E, S or G pillars. Consider the skin-in-the-game bond with as underlying benchmark the number of arrivals of the event. The payout of the skin-in-the-game bond will depend on the evolution of the benchmark and two types of triggers, with a tailored trigger penalty.

- *Yearly trigger.* The first trigger concerns the yearly number of events. This trigger is set at a level t_y, such that a penalty is imposed if the total number of events in a year exceeds t_y. The penalty can be determined by the issuer, ranging from a temporary coupon cancellation to a full write-down.



(a) Evolution of a continuous benchmark **(b)** Permanent coupon loss **(c)** Temporary coupon loss **(d)** Coupon withholding **(e)** Full write-down

Figure 1: The evolution of a continuous benchmark over time is sketched in **(a)**. The trigger level is only breached at the third payment date. The payout structure of a 5-year skin-in-the-game bond with annual coupon payment and as underlying the benchmark in **(a)** is pictured in combination with: **(b)** a permanent coupon loss penalty, **(c)** a temporary coupon loss penalty, **(d)** a coupon withholding penalty or **(e)** a full write-down penalty.

- *Cumulative trigger.* The second trigger concerns the cumulative number of events over the past duration of the bond. This trigger is a full write-down trigger and is set at level $t_c \cdot t$, for $t = 2, \ldots, T$. All future coupons and the notional redemption are wiped-out when the cumulative number of events up to time t exceeds $t_c \cdot t$. This way, an excessive number of yearly triggers is punished. Note that t_c can be fixed at $t_c = \infty$, in case one does not want an additional trigger.

An example is shown in Figure 2. The yearly trigger is hit at times 2 and 4. The bond is ultimately wiped-out at time 4, due to the activation of the cumulative trigger.

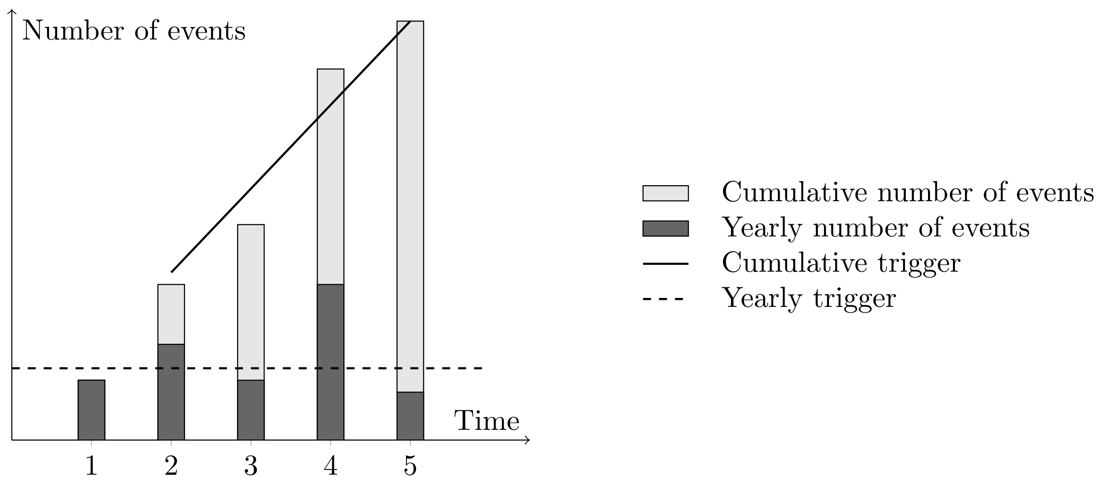


Figure 2: An illustration of the generic structure of a 5-year skin-in-the-game bond with a counting benchmark. The yearly trigger clause is activated at years 2 and 4. The cumulative trigger clause is activated at year 4.

2.2.2 Impact of an issuance on all parties involved

There are three major parties involved in the issuance of a skin-in-the-game bond: the issuer, the investor and the regulator. We shed light on the impact of the issuance of a skin-in-the-game bond on each of the three parties.

Issuer Similar to a CoCo bond's issuer, the issuer of a skin-in-the-game bond has a clear market driven incentive to optimize and stabilize the level of the benchmark underlying the bond. The issuer is said to have skin-in-the-game. Excessive risk-taking and mismanagement regarding the benchmark will hit the issuing company where it hurts; its cost of capital goes up as investors will require a higher yield. Together with the cost of capital, a company's reputational risk will increase. Unlike the issuer of a CoCo bond, the skin-in-the-game bond's issuer is obliged to pay out all future cash-flows of the bond, either to the investor or to the external fund.

Moreover, the issuance of a skin-in-the-game bond enhances transparency; in order to measure and monitor the benchmark, the issuer must be open on all measures taken and is forced to publish reliable information on its commitments. Intransparency will automatically translate into more uncertainty for investors and, again, the market will charge higher yields.

Investor Not only the issuer, but also the investor has skin-in-the-game. Where investors in SLBs speculate on *not* meeting sustainable targets, investors in skin-in-the-game bonds speculate on meeting the E, S and/or G related goals. In return for this skin-in-the-game, investors cash-in an above risk-free coupon on their invested amount.

Regulator/Government The third party involved in the issuance of a skin-in-the-game bond is the regulator or national government. This third party is essential for enforcing skin-in-the-game on the issuer side. Moreover, in case of a trigger event, with possibly large losses for society and damage to the environment, there are immediate funds available to mitigate these losses and (partially) cover the costs. The fund can be used to prevent a government bail-out with taxpayer's money; risks are shifted from taxpayers to private investors. Further, the cash is immediately available and not subject to a potentially lengthy procedure as it is often the case when an insured files a claim to his insurer.

3 The valuation of a skin-in-the-game bond

Inspired by the credit derivatives pricing approach for CoCos as described by De Spiegeleer and Schoutens (2012), we propose a valuation model for the skin-in-the-game bond. Compared to a standard corporate bond, which is subject to the issuer's bankruptcy risk, the trigger characteristic of the skin-in-the-game bond increases the probability for the investor to suffer a loss on the invested amount. To compensate the embedded trigger risk, the skin-in-the-game bond offers a higher yield than vanilla corporate debt issued by the same company. The yield offered to the investor on a standard corporate bond consists of the risk-free rate r and a credit spread c_s. This credit spread reflects the default risk of the bond; it is the extra yield investors request for the bankruptcy risk of the issuing company (Duffie and Singleton, 2003). For fixed income investors, the skin-in-the-game bond's pricing problem then boils down to determining the extra yield needed on top of the risk-free rate r and the credit spread c_s in order to accept the risk of facing a loss.

Standard corporate bond In absence of any embedded trigger risk, let the random variable C_t be the cash-flow at time t of a standard corporate bond with maturity T, notional N and yearly coupon payments at coupon rate c. In case of no default event, $C_t = c \cdot N$ for $t \in \{1, \ldots, T-1\}$ and $C_T = (1+c) \cdot N$. However, due to the default probability of the issuing firm, future values of these random variables are unknown. The expected value of future cash-flows, $\mathbb{E}_{\mathcal{Q}}[C_t]$ for $t \in \{1, \ldots, T\}$, under a pricing probability measure $\mathcal{Q}$, is therefore used for pricing purposes.

At first issuance, the bond trades at par, which means that the risk-neutral price P of the bond, given as the discounted expected payout under the pricing measure $\mathcal{Q}$, equals the nominal value N. For a bond subject to a risk-free rate r, one determines the additional yield c_s, needed in order to get investors to underwrite the default risk, by computing the coupon rate $c = r + c_s$, such that

$$P = \sum_{t=1}^{T} \frac{\mathbb{E}_{\mathcal{Q}}[C_t]}{(1+r)^t} := N, \tag{1}$$

and the bond trades at par.

Skin-in-the-game bond The skin-in-the-game bond bears an additional trigger risk and investors therefore require an extra yield, called the trigger spread t_s. The trigger spread can be seen as the yield difference between a skin-in-the-game bond (with trigger risk) and a standard corporate bond (without trigger risk), with the same characteristics.

Under the assumption that both r and c_s are known, one's interest is in calculating the trigger spread t_s. Therefore, let the random variable C_t be the cash-flow at time t, for $t \in \{1, \ldots, T\}$, of the skin-in-the-game bond. In absence of any trigger event, the value of the cash-flow at time t is identical to that of a standard corporate bond. However, on the occurrence of a trigger event, the future value of these cash-flows depends on the trigger penalty, fixed in the terms of the bond. At issuance, the future value of C_t, for $t \in \{1, \ldots, T\}$ is thus unknown, due to the trigger probability, and the expected value $\mathbb{E}_{\mathcal{Q}}[C_t]$ is used for pricing purposes. In order to incorporate the default probability of the firm, the expected cash-flows of a skin-in-the-game bond are subject to a discount rate $r+c_s$. One then determines the additional yield t_s, needed in order to get investors to underwrite the trigger risk, by computing the coupon rate $c = r+c_s+t_s$, such that

$$P = \sum_{t=1}^{T} \frac{\mathbb{E}_{\mathcal{Q}}[C_t]}{(1+r+c_s)^t} := N, \tag{2}$$

and the bond trades at par.

If both the risk-free rate r and the credit spread c_s are known, the only non-trivial value, needed to calculate the coupon rate and corresponding trigger level using Equation (2), is an estimate of the trigger probability at different points in time. To see this, consider a skin-in-the-game bond with a temporary coupon loss penalty. The probability that a cash-flow is paid out at time

t is equal to the probability that the trigger clause of the bond is *not* activated at that time. Suppose PT_t is equal to the trigger probability at time $t \neq T$, it then holds that

$$\mathbb{E}_{\mathcal{Q}}[C_t] = \mathrm{PT}_t \cdot 0 + (1 - \mathrm{PT}_t) \cdot c \cdot N = (1 - \mathrm{PT}_t) \cdot c \cdot N. \tag{3}$$

If we replace $\mathbb{E}_{\mathcal{Q}}[C_t]$, for each $t \in \{1, \ldots, T\}$, with an expression in function of the known trigger probability PT_t, we can solve Equation (2) for t_s.

Building a map from $\mathcal{P}$ to $\mathcal{Q}$ Calculating trigger probabilities is by far the most challenging task in pricing a skin-in-the-game bond. Moreover, Equation (2) requires these probabilities to be calculated under a pricing probability measure $\mathcal{Q}$. In practice, information on measure $\mathcal{Q}$ is often derived from market data such as option prices or spreads of credit default swaps (see e.g. Figlewski, 2018; Hull, 2015). Any probabilities derived from historical information will result in probabilities under a real-world probability measure $\mathcal{P}$, which is not used for pricing purposes. As the skin-in-the-game bond is not a traded instrument, we will not be able to calculate trigger probabilities under measure $\mathcal{Q}$ and so we are forced to make a rather strong assumption when mapping $\mathcal{P}$ to $\mathcal{Q}$.

A somewhat similar problem is studied in the credit scoring literature, namely the default risk of a company and the relationship between actual ($PD^{\mathcal{P}}$) and pricing ($PD^{\mathcal{Q}}$) default probabilities. There exists no unanimity on the exact form of this relationship, but one agrees in general that risk-neutral default probabilities are higher than actual default probabilities and that the actual default probability as a function of the pricing probability is increasing and convex (Hull et al., 2005; Berg, 2010; Heynderickx et al., 2016). Based on a dataset of European banks, Cariboni et al. (2011) empirically investigate the relationship between $PD^{\mathcal{P}}$ and $PD^{\mathcal{Q}}$. Consistent with other literature, they build a continuous and convex map that allows moving from one probability measure to another:

$$PD^{\mathcal{P}} = \exp\left[(PD^{\mathcal{Q}})^{1.39}\right] - 1. \tag{4}$$

The default of a firm results in a loss for investors in debt security that is issued by that firm. Similarly, the trigger of a skin-in-the-game bond results in a loss for the investors of the skin-in-the-game bond. Motivated by our need to have a closed-form relation, the similarity between default and trigger probabilities, and the effect of a default and trigger event, we find it reasonable to assume that the market will apply a same relationship as proposed in Equation (4) to trigger probabilities of skin-in-the-game bonds. In what follows, we will therefore use the relation in Equation (4) to transform trigger probabilities under measure $\mathcal{P}$ to trigger probabilities under measure $\mathcal{Q}$. In the next sections, we elaborate on two different methodologies to calculate these probabilities, through the use of two illustrative examples.

4 The ESG skin-in-the-game bond

Many (inter)national companies are nowadays being rated on their ESG performance by various third party providers, ranging from well-established, global data providers (e.g. MSCI, Bloomberg and Thomas Reuters) to niche ESG specialists (e.g. Sustainalytics, Vigeo Eiris and TruValue Labs) (Kumar and Weiner, 2019). Investors increasingly rely on ESG ratings as the basis of an investor engagement with the company (Huber and Comstock, 2017). The issuance of a skin-in-the-game bond linked to the ESG performance of the company provides the issuer with incentives to reach and maintain a favorable ESG rating, in order to, among other things, be attractive to new investors.

An extensive stream of research sheds light on the differences across the ratings published by the ESG rating providers (see e.g. Berg et al., 2020; Dorfleitner et al., 2015). A varying rating methodology, a different scope and coverage and the existence of discrete as well as continuous ratings hamper a comparison between the different rating agencies. Without a global ESG rating system, the below discussion of a skin-in-the-game bond with an ESG rating benchmark should merely be seen as an illustrative example of a skin-in-the-game bond with a tailored pricing technique.

Building upon the examples given in De Spiegeleer and Schoutens (2019), ESG skin-in-the-game bonds use the ESG rating of a company, provided by a particular rating agency, as the benchmark underlying the trigger mechanism of the bond. The bond triggers when the ESG rating of the company drops below a preset low level. This level must be determined according to the industry or sector in which the company operates. A hit of the trigger level then indicates that the issuer fails to deliver the E, S and/or G commitments realized by companies operating in a similar business. Besides the trigger level, the trigger penalty, maturity, frequency of coupon payments and notional of the bond need to be fixed.

4.1 ESG data

We use a European ESG rating dataset provided by Sustainalytics for the period January 2017 to September 2019[1]. Sustainalytics determines company-specific raw scores on 163 ESG-related indicators across the E (59), S (61) and G (43) pillars of sustainability. The individual scores range from 0 to 100, with a higher score indicating a better performance in managing the specific ESG issue. Using a proprietary weighting scheme, adapted to the specific characteristics of an industry, Sustainalytics aggregates raw indicator scores into an overall ESG rating for each of the $K = 3\,294$ European companies included in the dataset:

$$\mathrm{ESG}_k = \sum_{i=1}^{163} \text{raw score}_i \cdot \text{weight}_i, \tag{5}$$

for company $k = 1, \ldots, K$.

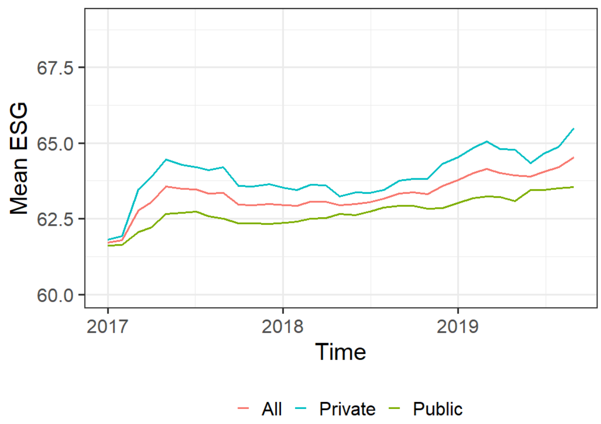
The majority of a company's raw scores are subject to annual revisions, which occur in line with the release of the company's annual report. A minority of indicators, related to controversial events such as employee or business ethics incidents, are continuously monitored by an in-house team of analysts and adjusted in response to ESG-related news, e.g., from news articles.

The Sustainalytics dataset is a monthly snapshot of all indicator scores for each firm. All firm's scores are released on the same date, typically occurring within the first week of the month. Due to the continuous adjustment of some indicators, the dates within the dataset do not necessarily coincide with the moment on which scores were really updated by the in-house team of Sustainalytics. As a result, the exact company-specific score on all indicators is only known at a finite series of data points, one for each month, and information in between dates is not available. Given these characteristics, we say that the available panel data on ESG indicator scores consists of intermittently observed, continuous-time processes (Wooldridge, 2009). In what follows, we will not work with the available time series of individual scores on the 163

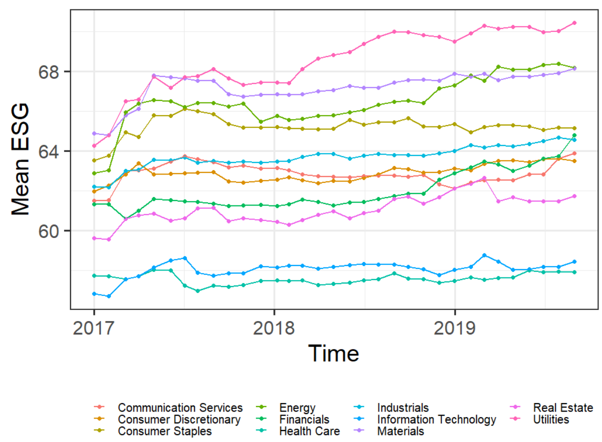
[1] More information can be found on `https://www.sustainalytics.com/esg-data/`.

indicators, but only with the time series of aggregated ESG ratings as calculated using Equation (5), on a monthly basis.

The companies in the dataset are subdivided into two categories (public or private) according to the company type and grouped into 11 sectors, according to the Global Industry Classification Standard (GICS) (S&P Global Market Intelligence, 2018). The evolution of the overall mean ESG rating between January 2017 and September 2019 can be found in Figure 3a, as well as the mean rating for both private and public firms. The evolution of the overall mean ESG rating for each of the 11 sectors is shown in Figure 3b. As illustrated in both figures, the mean ESG rating is rather stable over time, and heavily dependent on the sector in which the company operates.



(a) Mean ESG score



(b) Mean ESG score per sector

Figure 3: The mean ESG score, between January 2017 and September 2019, is presented in **(a)** for all companies as well as public and private companies and in **(b)** for each of the 11 sectors separately.

4.2 A valuation framework

The trigger probability of an ESG skin-in-the-game bond is determined by the probability that the issuing firm's ESG rating drops to or below the trigger level. The similarities between ESG ratings and credit ratings are striking and the literature on credit ratings is therefore of great use to model the evolution of a company's ESG rating. To apply the tailored methodology, it is convenient to transform the raw ratings of Sustainalytics into ESG rating categories, as shown in Table 1. On the basis of this transformation lies the distribution of companies within each MSCI rating category, as presented in Dahl and Larsen (2014)[2]. First, the companies in the available Sustainalytics dataset are ranked according to their ESG rating at the beginning of 2017. Next, the data percentiles from Dahl and Larsen (2014) are applied to the ranked dataset, which results in a subdivision of the companies into 7 categories. The given raw rating thresholds for the different categories are finally obtained from the ratings of all companies within a category.

Inspired by the literature on credit ratings, we model a company's movements, in continuous-time, between a finite set of ESG rating categories, using a first-order Markov multi-state model

[2]MSCI uses rating categories to indicate a company's ESG performance. More information can be found on https://www.msci.com/our-solutions/esg-investing/esg-ratings.

Table 1: Raw rating thresholds and data percentiles for Sustainalytics' ESG rating categories.

Rating category	C	CCC	B	BB	BBB	A	AAA
Raw rating	0-48	48-54	54-61	61-69	69-74	74-79	79-100
Data percentile	0-10	10-25	25-45	45-65	65-80	80-90	90-100

(Kalbfleisch and Lawless, 1985; Lando and Skodeberg, 2002; Mählmann, 2006). Suppose a company is in state $R(t)$ at time t, where $R(t)$ takes values in the state space

$$\mathrm{S} = \{\mathrm{C, CCC, B, BB, BBB, A, AAA}\}.$$

Let $P(s,t)$ be the $\mid \mathrm{S} \mid \times \mid \mathrm{S} \mid$ transition probability matrix with probabilities $p_{ij}(s,t)$ to transition from one ESG state i to another state j over a predefined time horizon $t-s$:

$$p_{ij}(s,t) = \Pr\left(R(t) = j \mid R(s) = i\right).$$

Under the first-order Markov assumption, the future rating state only depends on the current state and not on the full history of states. The transition intensities $q_{ij}(t)$ represent the instantaneous risk of moving from state i to state $j \neq i$, at time t:

$$q_{ij}(t) = \lim_{\delta t \to 0} p_{ij}(t, t+\delta t)/\delta t, \text{ for } i \neq j,$$

and

$$q_{ii}(t) = -\sum_{j \neq i} q_{ij}(t), \text{ for } i = 1, \ldots, \mid \mathrm{S} \mid.$$

We additionally assume a time-homogeneous model, in which $q_{ij}(t) = q_{ij}$ and Q is the transition intensity matrix. This results in a time-invariant transition probability matrix $P(t) = P(s, s+t) = P(0,t)$. Using Cox and Miller (1965), we know that

$$P(t) = \exp(Qt) = \sum_{k=0}^{\infty} \frac{Q^k t^k}{k!}. \tag{6}$$

The essential building block in the estimation of the trigger probability of an ESG skin-in-the-game bond is the rating transition probability matrix $P(t)$. As an example, if the trigger level is set at a BB rating, the probability that the bond triggers within the first year then equals the probability that the issuer's rating drops to either BB, B, CCC or C within that year.

We apply an estimation method based on the work of Kalbfleisch and Lawless (1985) and Jackson (2011) that provides us with a maximum likelihood estimate of the transition matrix P, when exact transition times and class occupancy in between observation times are unknown. To this intent, let k index the K individual firms in the available ESG dataset. The data of firm k consists of a series of time points and corresponding ESG categories: $\{(t_{k0}, R_{t_{k0}}),\ (t_{k1}, R_{t_{k1}}),\ \ldots,\ (t_{kn_k}, R_{t_{kn_k}})\}$. Note that the possible observation times $\{t_0, \ldots, t_n\}$ are fixed within the dataset, but not all firms are evaluated over the entire period from t_0 (January 2017) to t_n (September 2019).

Consider the pair of consecutively observed ESG states $R_{t_{kj}}$ and $R_{t_{kj+1}}$ of firm k. The contribution to the likelihood L_k of observing the rating history of firm k, from this pair, is the probability to be in state $R_{t_{kj+1}}$ at time t_{kj+1}, given that the firm was in state $R_{t_{kj}}$ at time t_{kj}, which is exactly

$$p_{R_{t_{kj}} R_{t_{kj+1}}}(t_{kj}, t_{kj+1}) = p_{R_{t_{kj}} R_{t_{kj+1}}}(t_{kj+1} - t_{kj}),$$

under the assumption of time-homogeneity. The first-order Markov assumption then results in the likelihood L_k of firm k:

$$L_k = \prod_{j=0}^{n_k-1} p_{R_{t_{kj}} R_{t_{kj+1}}}(t_{kj+1} - t_{kj}).$$

Under the assumption of independent rating paths for the different firms in the dataset, the full likelihood L is the product over all terms L_k:

$$L = \prod_{k=1}^{K} \prod_{j=0}^{n_k-1} p_{R_{t_{kj}} R_{t_{kj+1}}}(t_{kj+1} - t_{kj}) = \prod_{l=0}^{n-1} \prod_{i,j \in S} [p_{ij}(t_{l+1} - t_l)]^{n_{ijl}}, \tag{7}$$

where n_{ijl} is the number of firms in state i at time t_l and j at time t_{l+1}. Moreover, $L = L(Q)$; the likelihood depends on the transition intensity matrix Q via Equation (6). We refer to Kalbfleisch and Lawless (1985) for an in-depth discussion on the relation between L and Q.

We fit a time-homogeneous, first-order Markov multi-state model under the likelihood in Equation (7), using the implementation of Jackson (2011). The optimization is done using a Fisher scoring method as first described by Kalbfleisch and Lawless (1985). Additionally, following Jackson (2011), we model the effect of a vector $\boldsymbol{z_k}$ of time-independent explanatory variables on the transition intensities of firm k, using proportional intensities

$$q_{ij}(\boldsymbol{z_k}) = \exp\left(\beta_{ij}^{(0)} + \boldsymbol{\beta}_{\boldsymbol{ij}}^{\top} \boldsymbol{z_k}\right), \quad \text{for } i \neq j. \tag{8}$$

A skin-in-the-game bond will be issued by a specific company, so by including these covariates, we are able to model the benchmark on the most granular level available.

The impact of each covariate varies across the different transitions from state i to state j. The likelihood in Equation (7) is then maximized over the coefficients $\beta_{ij}^{(0)}$ and $\boldsymbol{\beta}_{\boldsymbol{ij}}^{\top}$. A likelihood ratio test shows that the model with both company type and sector as covariates performs significantly better than the model without or with only one of the covariates. By means of example, the results of these tests as well as the estimates of the parameters in Equation (8), for a public firm in the communication services sector, are summarized in A.

4.3 The trigger spread of an ESG skin-in-the-game bond

By means of example, we calculate the trigger spread of an ESG skin-in-the-game bond with characteristics as summarized in Table 2. The risk-free rate r and credit spread c_s are fixed at a chosen level. We assume that the issuing company's rating is only assessed at the time a coupon has to be paid. This means that a drop of the issuing company's ESG rating to or below the trigger level will not trigger the bond, if the rating recovers before the next coupon date. Due to the permanent coupon loss penalty, at each year, we also need to take into account the possibility that the bond already triggered in the years before.

Since coupons are paid annually, we use the one-year transition matrix to assess the trigger probability of the ESG skin-in-the-game bond. Using the methodology as described in Section

Table 2: ESG skin-in-the-game bond characteristics.

Characteristics	Bond-specific values
issuer	public firm in communication services sector
risk-free rate r	0.010
credit spread c_s	0.025
issue date	January 1, 2020
maturity date	January 1, 2025
notional N	100
coupon rate	c
coupon frequency	annual
initial rating	A
trigger level	BB
trigger penalty	permanent coupon loss

4.2, the one-year transition matrix for a public firm in the communication services sector is calculated on the available Sustainalytics dataset. As this dataset consists of historical ESG scores, the matrix in Table 3 contains transition probabilities under the real-world probability measure $\mathcal{P}$.

Table 3: One-year transition matrix P under $\mathcal{P}$, for a public firm in the communication services sector.

	C	**CCC**	**B**	**BB**	**BBB**	**A**	**AAA**
C	0.53213	0.18029	0.22725	0.05577	0.00409	0.00042	0.00005
CCC	0.12705	0.47922	0.30573	0.08110	0.00618	0.00065	0.00007
B	0.06587	0.10967	0.51331	0.27567	0.03119	0.00379	0.00050
BB	0.00884	0.02761	0.12200	0.67539	0.14099	0.02163	0.00355
BBB	0.00089	0.00364	0.01845	0.19021	0.62482	0.13169	0.03031
A	0.00009	0.00048	0.00263	0.03941	0.25367	0.58823	0.11549
AAA	0.00002	0.00012	0.00064	0.01078	0.08476	0.19875	0.70492

The probability that the ESG skin-in-the-game bond is triggered at the first coupon date equals the probability that the firm's rating, at issuance equal to A, is equal to either BB, B, CCC or C at time 1. Using the transition probabilities in Table 3, we find that the first year's trigger probability, under the $\mathcal{P}$-measure, ($\mathrm{PT}_1^{\mathcal{P}}$) is equal to

$$\mathrm{PT}_1^{\mathcal{P}} = 0.03941 + 0.00263 + 0.00048 + 0.00009 = 0.04261.$$

There are two scenarios that cause this particular ESG skin-in-the-game bond to be triggered at the second coupon date. First, if the bond was triggered at the first coupon date, time 1, it will still be triggered at the second date, since the trigger penalty is a permanent coupon loss. Second, given that the bond was not triggered at time 1, the bond will trigger when the firm's rating is equal to either BB, B, CCC or C, at time 2. Combining both scenarios, we find that the second year's trigger probability ($\mathrm{PT}_2^{\mathcal{P}}$) under the $\mathcal{P}$-measure is equal to

$$\mathrm{PT}_2^{\mathcal{P}} = 0.04261 + 0.08048 = 0.12309.$$

A similar procedure can be used to calculate the $\mathcal{P}$-measure trigger probabilities at later time points, which are presented in Table 4.

The transition matrix in Table 3 provides valuable information on the dynamics of the ESG profile of a given firm, and results in trigger probabilities under the real-world probability measure $\mathcal{P}$. For pricing purposes, we now transform these $\mathcal{P}$-measure trigger probabilities, to $\mathcal{Q}$-measure trigger probabilities, using the transformation as described in Equation (4). The results are again summarized in Table 4.

Table 4: Trigger probabilities under both the $\mathcal{P}$ and $\mathcal{Q}$ probability measure for an ESG skin-in-the-game bond with characteristics as given in Table 2.

	Year **1**	Year **2**	Year **3**	Year **4**	Year **5**
$\mathrm{PT}^{\mathcal{P}}$	0.04261	0.12309	0.20974	0.29175	0.36613
$\mathrm{PT}^{\mathcal{Q}}$	0.10174	0.21241	0.30324	0.37521	0.43258

Given the characteristics of the skin-in-the-game bond in Table 2, we can calculate the trigger spread using the formulas in Equations (2) and (3) and the trigger probabilities in Table 4. The trigger spread is determined as the additional yield t_s, needed in order to get investors to underwrite the trigger risk, by computing the coupon rate $c = r + c_s + t_s$ such that

$$P = \sum_{t=1}^{T} \frac{\mathbb{E}_{\mathcal{Q}}[C_t]}{(1 + r + c_s)^t} = \frac{0.89826cN}{1.035} + \frac{0.78759cN}{1.035^2} + \frac{0.69676cN}{1.0356^3} + \frac{0.62479cN}{1.035^4} + \frac{0.56742cN + N}{1.035^4}$$
$$:= N = 100.$$

This results in a value of $c = 0.048567$, such that the trigger spread equals $t_s = 0.013567$, or approximately 136 basis points (bps).

We repeat the valuation exercise on multiple ESG skin-in-the-game bonds, with a varying issuer's initial rating, trigger level and trigger penalty. The resulting trigger spreads of this exercise are summarized in Tables 5a to 5d. These trigger spreads are illustrative spreads for a possible format of a skin-in-the-game bond. We clearly observe that, dependent on the issuer's initial rating, trigger level and trigger penalty, the bond's trigger spread varies from almost negligible to a significant percentage, especially in the case of a full write-down penalty. Moreover, the larger the distance between the initial rating and the trigger level, the smaller the trigger spread.

Table 5: t_s in bps for a 5-year ESG skin-in-the-game bond with annual coupon payment, varying trigger penalties and trigger level (column). The issuer has initial rating (row).

(a) Permanent coupon loss

	C	**CCC**	**B**	**BB**	**BBB**	**A**
CCC	173					
B	107	223				
BB	40	90	228			
BBB	15	35	84	300		
A	6	16	39	136	424	
AAA	4	8	21	75	222	459

(b) Temporary coupon loss

	C	**CCC**	**B**	**BB**	**BBB**	**A**
CCC	100					
B	66	144				
BB	28	66	171			
BBB	12	27	69	251		
A	6	13	34	121	358	
AAA	3	7	18	68	197	414

(c) Coupon withholding

	C	**CCC**	**B**	**BB**	**BBB**	**A**
CCC	99					
B	66	144				
BB	29	66	171			
BBB	12	28	69	251		
A	6	13	34	121	359	
AAA	3	7	19	68	197	414

(d) Full write-down

	C	**CCC**	**B**	**BB**	**BBB**	**A**
CCC	1319					
B	857	1669				
BB	396	797	1763			
BBB	184	375	806	2279		
A	93	198	446	1255	3163	
AAA	53	118	273	796	1920	3448

The trigger spreads of ESG skin-in-the-game bonds with characteristics as fixed in Table 2, but different firm type (public or private) and different sector are given in B.

5 The nuclear skin-in-the-game bond

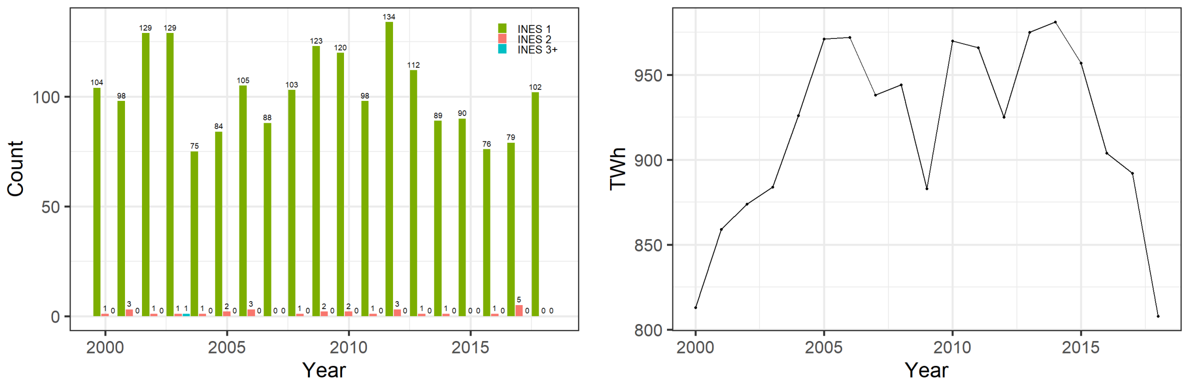
A nuclear power plant is a highly complex system, exposed to a set of diverse risk factors: mechanical breakdowns, human errors, tsunamis and many more. Consequently, there is always a (very small) probability of a nuclear disaster (Hofert and Wüthrich, 2012), which can lead to a massive amount of losses in human lives, damage to the environment and infrastructure and a declining economic activity in the contaminated area. The losses in case of a nuclear tail event are huge and potentially way beyond the loss absorbing capacity of the firm that owns the nuclear facility and/or the (re)insurer who covers (up to a certain limit) the damage caused (Nariai, 2016).

The severity of a nuclear and radiological event is rated on the International Nuclear Event Scale (INES), developed by the International Atomic Energy Agency (IAEA) in 1990 (IAEA, 2013). It divides nuclear events with safety significance into two categories and seven levels. Events rated INES level 4 to 7 are classified as accidents. These accidents result in a release of radioactive material into the environment and in the radiation exposure of workers and the public. As an example, Chernobyl (Ukraine, 1986) and Fukushima (Japan, 2011) are, so far in history, the only INES 7 events. Events rated level 1 to 3 are called incidents and may have no actual consequences for society, but they indicate that the measures put in place to prevent incidents and accidents did not function as intended.

Skin-in-the-game bonds can clearly play a beneficial role in the nuclear industry. Reactor-specific risks are revealed through a higher coupon charged by the market. Moreover, lax plant management is penalized by an increased cost of capital and so further investments in safety and risk controlling are incentivized. We define the number of INES events of a certain level as the benchmark underlying a nuclear skin-in-the-game bond. Within this example we thus discuss the valuation of a skin-in-the-game bond with a specific counting benchmark.

5.1 Nuclear event data

The data used in this example consists of INES rated nuclear events that took place between 2000 and 2018 in European nuclear power plants. The data is assembled on the basis of country reports published under the Convention on Nuclear Safety (CNS)[3]. For the covered period, a total of 1938 INES 1 events are included in the dataset, as being reported on European territory. In contrast, the data only contains 29 events of level 2, 1 event of level 3 and none of level 4 or higher. Since the occurrence of a nuclear event rated INES 3 or higher is very exceptional, we will, later on, model categories 3 to 7 as a single INES category, denoted as INES 3+. An overview of the yearly number of INES events as included in the data can be found in Figure 4a.



(a) Observed INES events

(b) Total net capacity

Figure 4: For the period 2000-2018, the total number of INES 1, INES 2 and INES 3+ rated events included in the dataset are shown in **(a)**. The yearly total net capacity in TWh electric energy as produced by the nuclear power plants included in the dataset is shown in **(b)**.

In addition to the number of INES events, we take into account the yearly net capacity in TWh electric energy as produced by the country's nuclear power plants (Ritchie, 2020). That way, we account for the fact that the more electric energy a country produces, the higher the likelihood on the occurrence of an INES event. The net capacity of a country thus indicates the exposure to potential events. In what follows, the number of INES events will always be put in perspective to the net capacity. The yearly total net capacity as included in the dataset is shown in Figure 4b.

5.2 A valuation framework

Based on the available INES data, we value three nuclear skin-in-the-game bonds with characteristics as summarized in Table 6. In all cases, the issuer is an average European nuclear power plant site with a fixed and constant yearly production of 10 TWh electric energy. Bond 1, 2 and 3 are respectively built on the number of INES 1, 2 and 3+ events as the benchmark. As

[3] The reports can be downloaded from `https://www.iaea.org/topics/nuclear-safety-conventions/convention-nuclear-safety/documents`

the consequences of a nuclear event get worse with increasing INES rating, the severity of the bonds' benchmarks increases significantly. It is then appropriate to also increase the severity of the penalty.

Table 6: Nuclear skin-in-the-game bond characteristics.

issuer		European NPP site with a yearly production of 10 TWh electric energy		
risk-free rate r				0.010
credit spread c_s				0.025
issue date				January 1, 2020
maturity date				January 1, 2025
notional N				100
coupon rate				c
coupon frequency				annual
		Bond 1	**Bond 2**	**Bond 3**
t_y	level	3 INES 1 events	1 INES 2 event	1 INES 3+ event
	penalty	temporary coupon loss	temporary coupon loss	full write-down
t_c	level	4 INES 1 events	1 INES 2 event	∞
	penalty	full write-down	full write-down	/

The valuation framework for the nuclear skin-in-the-game bond is based on the assumption that a Poisson process $\{N^{(i)}(t) \mid t \in (0, \infty)\}$ counts the number of INES level $i \in \{1, 2, 3+\}$ events that occur at a fixed intensity $\lambda^{(i)}$ per unit of time and unit of TWh electric energy. The same assumption is made in Hofert and Wüthrich (2012). For the scope of this illustrative example, it is sufficient to model the number of INES 1, INES 2 and INES 3+ events separately and independently. Using the Poisson process, the yearly trigger probability of a nuclear skin-in-the-game bond is modeled as the probability of occurrence of at least the number of INES i events within one year that triggers the bond, as fixed in the terms of the bond.

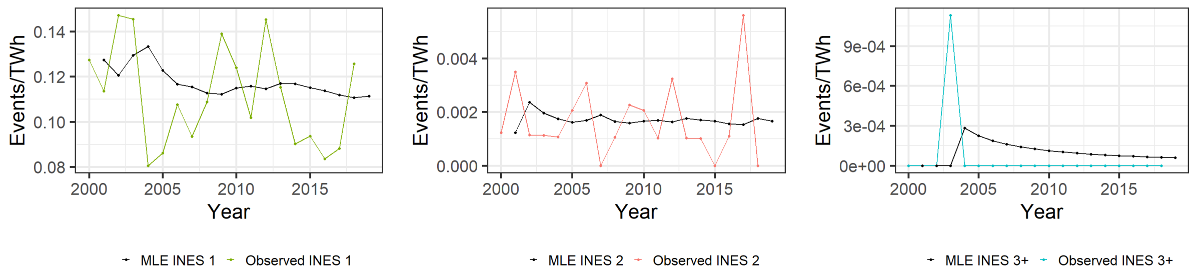
To this intent, define $M_t^{(i)} = N^{(i)}(t) - N^{(i)}(t-1)$, the number of INES i events that occur in year t, independently for different t and ω_t the total net capacity in TWh electric energy produced in year t. Under the formal definition of a Poisson process,

$$M_t^{(i)} \sim \text{Poisson}(\lambda^{(i)}\omega_t), \qquad \text{for } t \in \{2000, 2001, \dots\}. \tag{9}$$

We estimate $\lambda^{(i)}$ using the maximum likelihood estimator (MLE). The MLE of $\lambda^{(i)}$, estimated at time t is denoted as $\widehat{\lambda}_t^{(i)}$ and is equal to the sample mean of the yearly number of INES i events, per unit of TWh electric energy produced, yet available at the beginning of year t. This means for instance that $\widehat{\lambda}_{2019}^{(i)}$ is based on the set of observations from 2000 up to the year 2018: $\left\{\frac{M_{2000}^{(i)}}{\omega_{2000}}, \dots, \frac{M_{2018}^{(i)}}{\omega_{2018}}\right\}$, and given by

$$\widehat{\lambda}_{2019}^{(i)} = \frac{1}{2019 - 2000} \sum_{t=2000}^{2019-1} \frac{M_t^{(i)}}{\omega_t}.$$

The results are pictured in Figure 5a to 5c. We use $\widehat{\lambda}_{2019}^{(i)}$ as the fixed rate in Equation (9) in the remainder of this valuation exercise and denote it with $\widehat{\lambda}^{(i)}$. The values for different i are summarized in Table 7.



(a) Observed and MLE intensity of INES 1 events per year and unit TWh produced.

(b) Observed and MLE intensity of INES 2 events per year and unit TWh produced.

(c) Observed and MLE intensity of INES 3+ events per year and unit TWh produced.

Figure 5: The evolution of the observed and maximum likelihood estimated intensity of respectively INES 1, INES 2 and INES 3 and higher rated events is sketched in **(a)**, **(b)** and **(c)**, per unit TWh of produced electric energy, for European nuclear power plants.

Table 7: Maximum likelihood estimate for the intensity $\lambda^{(i)}$ as used in Equation (9).

	INES 1	INES 2	INES 3+
$\widehat{\lambda}^{(i)}$	0.11	0.0017	0.00006

5.3 The trigger spread of a nuclear skin-in-the-game bond

We calculate the trigger spread of the nuclear skin-in-the-game bonds with characteristics as summarized in Table 6. Using the intensity $\widehat{\lambda}^{(1)}$ from Table 7 and a fixed production of $\omega = 10$ TWh, the corresponding estimate for the expected number of yearly INES 1 events, in the years 2020 to 2025, is $\widehat{\lambda}^{(1)}\omega = 1.1$, with a standard deviation equal to $\sqrt{\widehat{\lambda}^{(1)}\omega} = 1.05$. The trigger of Bond 1 is set equal to 3 or more INES 1 events. That is, the bond triggers if the yearly number of INES 1 events of the plant is approximately more than 2 standard deviations away from the expected number of events. For Bond 2 and 3, the occurrence of an INES $\geqslant 2$ event is so exceptional, that these bonds already trigger at the occurrence of a single event.

Bond 1 The bond's yearly trigger level is set at 3 INES 1 events, with a temporary coupon loss penalty upon a trigger event. The probability at year $t = 1, \ldots, 5$ that a coupon is withheld due to the yearly trigger then equals

$$\mathrm{P}[M_t^{(1)} \geqslant 3] = \sum_{k=3}^{\infty} \frac{\exp(-\widehat{\lambda}^{(1)}\omega)(\widehat{\lambda}^{(1)}\omega)^k}{k!} = \sum_{k=3}^{\infty} \frac{\exp(-1.1)(1.1)^k}{k!} = 0.09958.$$

This is also the real trigger probability at time 1, $\mathrm{PT}_1^{\mathcal{P}}$. Additionally, the bond triggers when the cumulative number of events exceeds $4 \cdot t$ INES 1 events, for $t = 2, \ldots, 5$. As an example, at time $t = 2$ we have that

$$\begin{aligned}\mathrm{P}[N^{(1)}(t) - N^{(1)}(0) \geqslant 4t] = \mathrm{P}[M_1^{(1)} + M_2^{(1)} \geqslant 8] &= \sum_{k=8}^{\infty} \frac{\exp(-\widehat{\lambda}^{(1)}\omega t)(\widehat{\lambda}^{(1)}\omega t)^k}{k!}, \\ &= \sum_{k=8}^{\infty} \frac{\exp(-2.2)(2.2)^k}{k!} = 0.00198.\end{aligned}$$

Since the yearly and cumulative trigger are not mutually exclusive, we have a final trigger probability at year 2 equal to

$$\begin{aligned}\mathrm{PT}_2^{\mathcal{P}} &= \mathrm{P}[M_1^{(1)} \geqslant 3 \text{ or } M_1^{(1)} + M_2^{(1)} \geqslant 8], \\ &= \mathrm{P}[M_1^{(1)} \geqslant 3] + \mathrm{P}[M_1^{(1)} + M_2^{(1)} \geqslant 8] - \mathrm{P}[M_1^{(1)} + M_2^{(1)} \geqslant 8, M_2^{(1)} \geqslant 3], \\ &= 0.09958 + 0.00198 - 0.00172 = 0.09984.\end{aligned}$$

The trigger probabilities at later years can be found in Table 8. Note that at year 5, we need to distinguish between the situation where the coupon is not paid due to a yearly trigger, but the notional is paid and the situation where the bond is wiped-out completely.

In order to calculate the trigger spread, we transform the trigger probabilities under the measure $\mathcal{P}$ to trigger probabilities under the pricing measure $\mathcal{Q}$, using again Equation (4). Equations (2) and (3) then ultimately result in a trigger spread equal to 106 bps.

Bond 2 We use the same procedure as in the case of Bond 1, to calculate the trigger probabilities of Bond 2. The results are summarized in Table 8. Bond 2 has a trigger spread equal to 29 bps.

Bond 3 The third bond is immediately withdrawn upon a trigger event: the occurrence of an INES 3+ event. For the first year, the trigger probability is equal to

$$\mathrm{PT}_1^{\mathcal{P}} = \mathrm{P}[M_1^{(3+)} \geqslant 1] = \sum_{k=1}^{\infty} \frac{\exp(-0.0006)(0.0006)^k}{k!} = 0.00060.$$

For the second year, we have to take into account the possibility that the bond already triggered in the first year. We then have, using the independent increment property of a Poisson process,

$$\begin{aligned}\mathrm{PT}_2^{\mathcal{P}} &= \mathrm{P}[M_1^{(3+)} \geqslant 1 \text{ or } M_2^{(3+)} \geqslant 1] \\ &= \mathrm{P}[M_1^{(3+)} \geqslant 1] + \mathrm{P}[M_2^{(3+)} \geqslant 1] - \mathrm{P}[M_1^{(3+)} \geqslant 1]\mathrm{P}[M_2^{(3+)} \geqslant 1] = 0.00120.\end{aligned}$$

A similar reasoning is used for the trigger probability at years 3, 4 and 5, as given in Table 8. The trigger spread of Bond 3 amounts 32 bps.

Table 8: Trigger probabilities under both the $\mathcal{P}$ and $\mathcal{Q}$ probability measure and trigger spreads (in bps) for the nuclear skin-in-the-game bonds with characteristics as given in Table 6.

		Year **1**	Year **2**	Year **3**	Year **4**	Year **5** cN	Year **5** N	t_s
Bond 1	$\mathrm{PT}^{\mathcal{P}}$	0.09958	0.09984	0.10119	0.10135	0.10138	0.00202	106
	$\mathrm{PT}^{\mathcal{Q}}$	0.18379	0.18412	0.18582	0.18602	0.18605	0.01150	
Bond 2	$\mathrm{PT}^{\mathcal{P}}$	0.01686	0.01700	0.01738	0.01741	0.01742	0.00057	29
	$\mathrm{PT}^{\mathcal{Q}}$	0.05268	0.05300	0.05384	0.05392	0.05393	0.00463	
Bond 3	$\mathrm{PT}^{\mathcal{P}}$	0.00060	0.00120	0.00180	0.00240	0.00300	0.00300	32
	$\mathrm{PT}^{\mathcal{Q}}$	0.00481	0.00791	0.01059	0.01302	0.01528	0.01528	

From Table 8, we observe on the one hand that the trigger spread of Bond 1 is three times higher than the trigger spread of Bond 2 and 3. Though the trigger penalty of Bond 2 is more severe, the significantly higher probability on an INES 1 event, compared to INES $\geqslant 2$ events, results in a higher trigger spread. On the other hand, the trigger spread of Bond 2 is comparable to that of Bond 3. Even though the probability on an INES 2 event is higher than the probability on an INES 3+ event, the stringent penalty of Bond 3, i.e., the immediate write-down of the bond on the occurrence of an INES 3+ event, balances the risk in both products.

All calculations in this example start from an average European power plant. We therefore consider the calculated spreads as indicative for the market average. In reality, all issuers of nuclear skin-in-the-game bonds will have different spreads, calculated in the same way, but based on the issuer specific history of INES events and electric energy produced. The market mechanism will ultimately point out the less safe power plants by charging a higher coupon rate than the market average we calculated.

6 Conclusion

To conclude, we argue for the implementation of a sustainable debt instrument with an embedded financial penalty related to E, S and/or G commitments. The skin-in-the-game bond provides clear incentives for the issuer to reduce excessive risk-taking, maintain a favorable benchmark value and bring transparency. It also provides a mechanism for investors to gain above risk-free returns in compensation for clearly upfront specified risks. The involvement of a third party fund makes sure that collateral is available in case of a major disaster to reduce negative externality and make investments for recovery possible.

In general, the issuance of a skin-in-the-game bond should result in aligned incentives for both the issuer and investor. The skin-in-the-game bond improves on the currently existing green, social, sustainability and sustainability-linked bonds, by enforcing skin-in-the-game, which fights moral hazard risk. Moreover, the skin-in-the-game bond uses the market mechanism as a means to achieve an objective view on the underlying risks; financial markets will charge higher coupons if it is likely that promises turn out differently than promoted.

A Modeling Results of Section 4.2

Table 1: Results of the Likelihood Ratio test for different models.

Models		Test		
Covariates −2logL	Covariates −2logL	−2logLR	df	p-value
None 23484.58	Type 23405.52	79.06	37	6.957452e-05
	Sector 22992.60	491.98	370	2.131873e-05
	Type & Sector 22914.54	570.04	407	1.574531e-07
Type 23405.52	Type & Sector 22914.54	490.98	370	2.433809e-05
Sector 22992.60	Type & Sector 22914.54	78.06	37	9.290669e-05

Table 2: Coefficient estimates of Equation (8) and corresponding transition intensities for a public firm in the communication services sector. The communication services sector serves as the baseline for the categorical sector covariate.

Ratings				
From	To	Baseline $\beta_{ij}^{(0)}$	Type Public β_{ij}	Intensity q_{ij}
C	C			-6.9182×10^{-1}
C	CCC	-1.6955	0.6032	3.3544×10^{-1}
C	B	-1.0939	0.0620	3.5632×10^{-1}
C	BB	-9.5926	-1.1382	2.1861×10^{-5}
C	BBB	-11.2047	0.3853	2.0008×10^{-5}
C	A	-18.5800	6.6076	6.3162×10^{-6}
C	AAA	-11.0454	-8.0566	5.0595×10^{-9}
CCC	C	-1.3149	-0.1542	2.3013×10^{-1}
CCC	CCC			-8.4710×10^{-1}
CCC	B	-0.3038	-0.1793	6.1687×10^{-1}
CCC	BB	-8.8102	-0.4652	9.3701×10^{-5}
CCC	BBB	-10.6971	-7.6745	1.0503×10^{-8}
CCC	A	-10.8585	-1.1851	5.8821×10^{-6}
CCC	AAA	-∞	-∞	0
B	C	-2.2490	0.0257	1.0825×10^{-1}
B	CCC	-1.3383	-0.2221	2.1005×10^{-1}
B	B			-8.1090×10^{-1}
B	BB	-0.5766	-0.1316	4.9253×10^{-1}
B	BBB	-10.0672	-0.5014	2.5711×10^{-5}
B	A	-11.3576	-0.1581	9.9723×10^{-6}
B	AAA	-11.4032	-8.0703	3.4895×10^{-9}
BB	C	-11.8335	-2.4984	5.9667×10^{-7}
BB	CCC	-3.8245	0.2624	2.8379×10^{-2}
BB	B	-1.6999	0.1372	2.0956×10^{-1}
BB	BB			-4.7195×10^{-1}
BB	BBB	-1.2939	-0.2069	2.2295×10^{-1}
BB	A	-4.1643	-0.3419	1.1040×10^{-2}
BB	AAA	-20.2213	8.5380	8.4335×10^{-6}
BBB	C	-∞	-∞	0
BBB	CCC	-18.7929	6.3055	3.7739×10^{-6}
BBB	B	-20.1932	8.5491	8.7706×10^{-6}
BBB	BB	-0.9419	-0.2495	3.0380×10^{-1}
BBB	BBB			-5.5211×10^{-1}
BBB	A	-2.2293	0.7164	2.2027×10^{-1}
BBB	AAA	-4.7937	1.2191	2.8026×10^{-2}
A	C	-∞	-∞	0
A	CCC	-10.4709	-8.5611	5.4263×10^{-9}
A	B	-11.0122	-0.8122	7.3237×10^{-6}
A	BB	-8.5262	-0.6281	1.0576×10^{-4}
A	BBB	-0.9106	0.0667	4.3003×10^{-1}
A	A			-6.0823×10^{-1}
A	AAA	-2.0069	0.2814	1.7808×10^{-1}
AAA	C	-∞	-∞	0
AAA	CCC	-10.8334	-8.2260	5.2797×10^{-9}
AAA	B	-∞	-∞	0
AAA	BB	-10.0375	-1.3356	1.1501×10^{-5}
AAA	BBB	-10.9431	8.2506	6.7711×10^{-2}
AAA	A	-1.4810	0.3075	3.0928×10^{-1}
AAA	AAA			-3.7701×10^{-1}

B ESG skin-in-the-game bond trigger spreads for different company type and sector

In Table 1, the trigger spread of an ESG skin-in-the-game bond with characteristics as fixed in Table 2, but varying company type and sector, is given. We consistently observe that the trigger spread for private companies is higher than for public companies, regardless of the sector. Also, comparing the results with the sector specific evolution of the mean ESG in Figure 3b, we see that sectors with an overall increasing ESG level (e.g., Utilities and Energy) have lower spreads than sectors with a rather flat ESG evolution (e.g., Health Care and Consumer Staples).

Table 1: The trigger spread in bps of an ESG skin-in-the-game bond, with characteristics as fixed in Table 2, for firms with varying company type (column) and sector (row).

	Public	Private
Communication Services	136	162
Consumer Discretionary	199	286
Consumer Staples	314	407
Energy	112	294
Financials	102	141
Health Care	287	444
Industrials	128	189
Information Technology	112	173
Materials	178	220
Real Estate	122	237
Utilities	103	169

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