The new bonds on the block - Analyzing alternative green bond designs using a simulation-based approach

Abstract

The effects of climate change are becoming more apparent and with that the need to act. Meeting the announced pledge to limit the effects of climate change requires large financial resources, for which there is still a financing gap. Hence, finding efficient financing instruments is an important element to combat climate change. In this paper, we compare different green bond designs including fixed-rate, carbon-linked, inflation-linked, and convertible (green) bonds. We assume that the proceeds are invested into an emission-reducing project thus generating returns in form of saved CO_2 certificates. The carbon price is assumed to follow a geometric Brownian motion simulating a general optimal stopping time problem for the start of the investment project. Our simulation results indicate that most alternative bond designs do not set superior incentives compared to traditional green fixed-rate bonds. The only design that outperforms fixed-rate bonds, are green carbon-linked bonds following a coupon design inversely linked to the development of carbon prices. This is surprising given the latest issuance of green inflation-linked and green convertible bonds. Thus, the findings question whether alternative and more complex green bond designs are the right tool to combat climate change.

Keywords: Green bond, inflation-linked bond, carbon-linked bond, convertible bond, optimal stopping, emission-reducing projects, optimal corporate investment, climate finance, green finance, carbon finance

1. Introduction

Climate change and its expected implications from sea level rise to droughts will threaten a vast amount of people and their livelihoods (Nordhaus, 2019; Tol, 2009). As the effects of climate change are becoming more apparent e.g., by droughts or low tides such as in the Rhine river in August 2022 (Abdelnour, 2022), the public is more open to financing the green transition. Nonetheless, public support is partly dependent on the preservation of current living standards (van der Wiel et al., 2022; Hojnik et al., 2021). Meeting the required financing goals is challenging in the current high-inflation market, which is coupled with the fear of recession and thus higher default probabilities of governments and corporates alike (McCollum et al., 2018). One of the most important debt finance instruments are bonds that are issued by both private corporations and public institutions. There are many different forms starting from the "standard" fixed-rate bond with a recurring fixed coupon to the convertible bond with equity-like characteristics (Choudhry, 2010). In 2007, the European Investment Bank issued a new bond type in the form of "green bonds" following the objective to finance green projects (Ferrer et al., 2021). Since its inception, the green bond volume grew rapidly to an issuance volume of USD 259 bn in 2019 — still, it remains a fraction of the total bond market (Ferrer et al., 2021; Flammer, 2021). While the green bond market continues to grow, it does not come without shortcomings. In particular, concerns about governance and green labels lead to skepticism of investors and environmentalists (Dorfleitner et al., 2022; Flammer, 2020). Yet, climate experts believe that there still is a large financing gap to reach the aspired target of governments (McCollum et al., 2018). Thus, a functioning green bond market is crucial to support the available financial resources (Heine et al., 2019). The first green bond had a traditional fixed-rate bond structure with a coupon rate at a fixed interest rate (EIB, 2022). Following the developments of the traditional bond market, various forms of green bonds emerged, which are:

1. Fixed-rate green bond (e.g. Flammer, 2021)
2. Carbon-linked green bond (e.g. Worldbank, 2008a)
3. Inflation-linked green bond (e.g. French-Treasury, 2022)
4. Convertible green bond (e.g. NEOEN, 2022)

Given the higher complexity of carbon-linked, inflation-linked, and convertible green bonds, the question remains whether they set superior incentives for investors compared to "traditional" fixed-rate bonds offsetting the negative effects of higher complexity. In this article, we ask the question of which bond structure sets the appropriate incentives for issuers and spurs demand for green bonds and thus funding potential for green projects. To do so, we define an emission-reducing project that is financed by the issuance of a green bond. The return of the project is based on the saved emission certificates and thus we calculate a project net present value (NPV). We compare a green fixed-rate bond to a green inflation-linked bond by applying a simulation-based approach.

Our results indicate that projects financed by inflation-linked and convertible bonds do not lead to higher NPV or earlier execution of the project. However, carbon-linked bonds with a coupon structure inversely linked to the carbon price development offer a slight advantage compared to fixed-rate bonds. Thus, our paper has both theoretical and practical implications. Our approach offers a replicable method to compare different bond structures. From a practical point of view, we question the need to issue green inflation-linked and convertible bonds given their higher complexity. This paper is organized as follows: Section two defines the main properties and current research on the different green bonds, the carbon market, and the need for financing. Section three describes the model setting including the specific bond pricing. This is followed by the simulation-based implementation of the model in section four. Lastly, we conclude our findings and point to potential areas for further research.

2. Literature review and current trends

2.1. Financing needs to combat climate change and current market conditions

The transition to a “green(er)” economy does not come without significant investments into technology and infrastructure supporting a net-zero economy (Fankhauser et al., 2016). Even though scholars and intergovernmental organizations debate about the exact financing needs and allocation, most agree that there are still major financing gaps to reach the proclaimed national targets, the 2 degrees target or even the net zero target (Roberts et al., 2021; Rozenberg and Fay, Zamarioli et al., 2021; Hong et al. 2020; McCollum et al., 2018; Fankhauser et al., 2016; IEA, 2021). Modeling different scenarios, McCollum et al. (2018) estimate that there is a yearly financing gap of $ 130-480 bn until 2030. The gap becomes apparent looking at the unmet pledge of developed countries to raise $ 100 bn per year until 2020 for climate actions of developing countries (Den Elzen et al., 2011, Timperley, 2021; Roberts et al., 2021). Moreover, the European Central Bank believes that the gap is likely to widen due to the three phenomena of “climateflation”, “greenflation” and “fossilflation” (Schnabel, 2022).

Green bonds can be one part of the solution as they are debt-financing instruments that can be issued both by the government and corporates. In addition to this, the market for bonds is mature and market participants are familiar with its dynamics (Ning et al., 2022; Ng and Tao, 2016; Tolliver et al., 2019; European Commission, 2016; IEA, 2021). The OECD points out that the long-term orientation and low-risk asset class of bonds correspond to the low-carbon investment opportunities and are thus suitable to finance actions against climate change (Kaminker and Stewart, 2012; OECD, 2021). Finally, Sartzetakis (2021) argues that (partial) debt financing is an instrument for justice and equity to deal with the inter-generational challenge of climate change (Sartzetakis, 2021). The potential of green bonds to narrow the financing gap is also recognized by the OECD and other intergovernmental actors (IEA2022, 2022; European Commission, 2016). Hence, the question of which green bond structure is the most efficient one to close the gap becomes crucial.

2.2. Carbon prices and European-trading scheme

The EU was one of the first areas in which carbon pricing was introduced and constituted the largest carbon market in terms of covered emissions until 2021 before being surpassed by China (Nogrady et al., 2021). In general, putting a price on carbon is the attempt to include the "social cost" of emissions in the price of the good (Stiglitz, 2019). In addition, setting a price gives a direct incentive for emitters to reduce their footprint in order to save costs. As a result, investing in technology to reduce CO_2 emission e.g. by financing in production facilities that require less energy for the same output generates a return based on the price of the CO_2 which would otherwise have to be paid. There are two theoretical approaches on how to put a price on carbon. The first one is to implement a tax on carbon similar to other consumption-based taxes (Murray and Rivers, 2015; Andersson et al., 2015). The second one is to introduce some form of a "cap-and-trade" system, in which corporates need to have sufficient CO_2 certificates to compensate for their emissions. In this paper, we will focus on "cap-and-trade" systems[1] as they are widely implemented across the globe. Moreover, we focus on Europe as it is the most liquid and highly valued carbon market (Nordeng, 2022; Zhu et al., 2017).

More than 15 years ago, back in 2005, the European Union implemented the first cross-country emission trading system (ETS). As stated above, the system is based on the so-called "cap-and-trade" mechanism. In this system, emission certificates are issued which amount to one ton of CO_2-equivalent[2] emission per certificate. "Cap" stands for the design to incrementally reduce the number of certificates that are freely allocated to polluting companies. "Trade" accounts for the market characteristic that certificates can be traded between companies for a price that is formed by the market (Hintermann, 2010). The ETS system does not encompass all potential emitters but companies from energy-intensive industries, power generation, commercial aviation, and some basic materials sectors. The companies included in the ETS must cover all their CO_2 emissions either with their (freely) allocated certificates or by buying additional ones. The certificates can either be bought in auctions or outright from other emitters that have a surplus of certificates (European Commission, 2022). Those certificates are called emission allowances (EUA) and are traded in the future and spot market at the

[1] Please see Tvinnereim (2014) or Venmans et al. (2020) for an overview of major cap-and-trade markets around the world.
[2] CO_2 equivalent is used to make greenhouse gas emissions comparable — thus different gases are converted according to their global warning potential (Eurostat, 2022).

two major stock markets of EEX Leipzig or ICE London (Stefan and Wellenreuther, 2020). In the rest of the paper, we focus on EUAs as they constitute the largest and most liquid carbon market (Ibikunle et al., 2016).

Even though more and more countries are introducing one of the mechanisms to price carbon, experts largely agree that the current carbon price level across the world remains too low while having experienced a significant increase in the past years (Klenert et al., 2018; IEA2022, worldbank, 2022; Nogrady et al., 2021; IEA, 2022a). In August 2022, the price for one certificate in the EU was fluctuating in the range of € 80-90 (Statista, 2022). Looking at the last year, the price averages at € 52 which is an increase of more than 110% compared to 2020 (Bloomberg, 2022; Umweltbundesamt, 2022). The International Energy Agency (IEA) estimates that a price of \$ 140 /t CO_2 by 2030, \$ 205 /t CO_2 by 2040, and \$ 250 /t CO_2 is required in developed economies to reach the net zero emission ambition by 2050 (IEA, 2022b)[3]. Similar to other commodity markets, the price of carbon certificates follows various factors and authors have developed models to simulate the prices (Ji et al., 2019; Bloch, 2011; Benz and Trück, 2009; Nazifi, 2013; Hao et al., 2020; Sun and Huang, 2020; Li et al., 2022; Lamphiere et al., 2021). Scholars identify six major determinants of the development of EUA prices: 1) Energy prices incl. oil, 2) CERs prices, 3) Weather conditions, 4) Economic activity, 5) Market design (institutional design of ETS e.g. set cap) and 6) Other external factors such as global climate negotiations (among others Alberola and Chevallier, 2009; Batten et al., 2021; Broadstock and Cheng, 2019; Creti et al., 2012; Zhu et al., 2017; Alberola et al., 2008; Mansanet-Bataller et al., 2007; Christiansen et al., 2005; Stoll and Mehling, 2021; Mintz-Woo et al., 2021; Batten et al., 2021). To summarize, with the introduction of the ETS, many corporates in Europe have to pay for the right to emit greenhouse gases. As a result, investments in emission-reducing projects yield additional returns based on their potential to reduce emissions and thus require fewer certificates.

2.3. Green bonds

Since their inception in 2007, the green bond market soared across the globe to an issuance size of \$ 259 bn (Ferrer et al., 2021). Mirroring most characteristics of conventional bonds, green bonds have been rapidly capitalized by investors in the financial market as an innovative debt-financing instrument (Russo et al., 2021). Heine et al. (2019) consider green bonds as a key element to combat climate change supplementing carbon pricing. In addition, the authors argue that there are interaction effects between green bonds and carbon pricing as investments in emission-reducing projects are likely to grow if the carbon price rises and thus increase demand for green bonds (Heine et al., 2019). In lockstep with the soaring green bond issuance, various forms of green bonds emerged, which require

[3] In last year's report the IEA expected a price of \$ 130 CO_2 for 2030 - all other unchanged (IEA, 2021)

a definition and delimitation. Generally, the key differentiator to conventional bonds is the use of proceeds clause which is a requirement to use the generated funds to finance climate-friendly projects (ICMA, 2022). Green bonds are used as a private and public debt-financing tool and have adopted many of the characteristics of the traditional bond market. To the best of our knowledge, the majority of green bonds issued are green fixed-rate bonds, which are bonds that pay a pre-defined coupon until maturity. In addition to this, green inflation-linked and green convertible bonds have gained momentum in recent years (e.g. NEOEN 2022; French Treasury 2022). A more exotic bond design directly linked to the development of the carbon market was tested soon after the issuance of the first green bond but failed to gain much adoption in practice (Worldbank 2008a). Additional green bond structures are likely to emerge based on innovations in the traditional bond market. In this paper, we focus on five green bond designs which will be described in the next sections. From a policy perspective, the rationale for the issuance of green bonds is clear — to support the efforts to combat climate change. Rationales from issuers and investors in green bonds are less clear. Focusing on corporate green bond issuers, Flammer (2021) identifies three potential arguments for issuing green bonds which are signaling, green-washing, and reducing the cost of capital. She concludes that only the signaling effect finds support analyzing the abnormal returns of companies issuing green bonds (Flammer 2021).

The demand for green bond issuance is accompanied by a surge in research papers on this topic. Nonetheless, influential authors argue that research on green bonds is still in its early stages (e.g. Flammer, 2021; Larcker and Watts, 2020). The most dominant research stream evolves around the question of whether green bonds yield lower returns than conventional bonds. Despite the significant number of articles, the results remain inconclusive. Some studies point toward a positive effect (e.g Baker et al., 2018; Zerbib, 2019), while other authors can neither find positive nor negative effects (e.g. Larcker and Watts, 2020; Hachenberg and Schiereck, 2018) and finally again others find a negative effect (e.g. Karpf and Mandel, 2017; Bachelet et al., 2019). In recent years, the study of Flammer (2021) on corporate bonds in the time frame of 2013 to 2018 and Löffler et al. (2021) strengthen the argument that there is no greenium. Apart from the research on greenium, four key green bond research streams can be identified. Firstly, authors investigate the connectedness to other financial instruments analyzing the interplay of green bonds with stocks (e.g. Ferrer et al., 2021; Reboredo and Ugolini, 2020), other bond markets (e.g. Ferrer et al., 2021; Reboredo and Ugolini, 2020), commodities (e.g. Reboredo and Ugolini, 2020) and other assets (e.g. Saeed et al., 2021). Secondly, market characteristics including the issuance size (e.g. Russo et al., 2021; Löffler et al., 2021), country-specific development, and issuer-specific characteristics (e.g. Banga, 2019) are analyzed. Thirdly, a smaller number of scholars conduct research on governance-related topics, incl. the third-party certification of bonds (e.g. Immel et al., 2021 and Park, 2018). Finally, several authors explore the impact of green bond issuance on issuers including their financial performance, stock performance, ownership structure and environmental performance (e.g. Flammer, 2021).

Notwithstanding the soaring market, green bonds do not come without shortcomings. Scholars criticize various governance issues due to the private governance regime (e.g. Flammer, 2020; Dorfleitner et al., 2022; Flammer, 2021; Park, 2018). One of the fundamental issues starts with the definition of what classifies as “green” as there is no holistically applied definition. In addition to this, there is no rating or classification on the “greenness” of different bonds (Hachenberg and Schiereck, 2018; Hyun et al., 2019). Comparing the yield spread of conventional and green bonds, Simeth (2022) showed that second-party opinions lower the difference. This supports the hypothesis that governance issues are inherent in the green bond market as the market requires additional verification.

Still, to the best of our knowledge, there is no study that compares different green bond structures regarding their potential to set incentives to invest in emission-reducing projects. Given the inherent governance issues of the green bond market, we believe that finding financial incentive structures for investors is important to support the next phase of green bond issuance.

2.4. Inflation-linked bonds

Given the current high-inflationary market conditions in many economies around the world, investors search for ways to mitigate the inflation risk. A product that offers protection against inflation is inflation-linked bonds (also known as inflation-indexed bonds) (Choudhry et al., 2005; Price, 1997). Inflation-linked bonds are by no means a new instrument with initial issuance in 1780 during the revolutionary war in the US (Shiller, 2003). Since then, the US Treasury Inflation-Protected Securities have experienced strong growth rates starting with a volume of \$ 33 bn in 1997 (1% of total outstanding treasury securities) to reaching \$ 1,789 bn in July 2022 accounting for 7.7% of total outstanding US Treasury Securities. As indicated by the name, inflation-linked bonds are adjusted to follow the development of inflation and are part of the broader category of index-linked bonds. There are many different forms of inflation-linked bonds but the main mechanisms are the adjustment of coupon or principal to inflation. Smith (2010) differentiates between “P-linkers” and “C-linkers” indicating that the design either adjusts the principal or coupon to inflation. Originally issued as government security, inflation-linked bonds are also used by corporates with various structures applied e.g. the US Treasury TIPS apply a structure in which the principal is adjusted according to inflation (Campbell et al., 2009). Key rationales for issuing of inflation-linked bonds are the hope to lower financing cost and to broaden the investor base (Reschreiter 2004; Sack and Elsasser 2004; Danish-National-Bank, 2022; Garcia and van Rixtel, 2007). From the point of investors, scholars argue that inflation-linked bonds are a hedge against inflation and thus can be used for portfolio diversification (e.g. Bodie, 1988; Hammond, 2002; Kothari and Shanken, 2004; Bardong and Lehnert, 2004). Another field of scholarly interest is focused on defining an appropriate price for inflation-linked bonds with the seminal work of Jarrow and Yildirim (2003) and Mercurio and Moreni (2006). In addition, other authors such as Fleckenstein et al. (2014) investigate potential mispricing and arbitrage opportunities in the inflation-linked bond market.

Green inflation-linked bonds are rather new compared to other bond designs. In May 2019, Orsted, a Danish energy company placed a £ 250 M green inflation-linked bond based on the development of the UK consumer prices (ISIN: XS1997071086). Three years later, the French Treasury was the first non-private issuer with a € 4 bn bond linked to the Harmonized Consumer Price Index (HCPI) (ISIN: R001400AQH0). Nevertheless, the market has not yet started to see many additional issuances (see table 1). Similarly, to the best of our knowledge, there is no paper explicitly addressing the topic of green inflation-linked bonds. We briefly outline the main characteristics of both green inflation-linked bonds to improve the understanding of the model setup. Orsted's green inflation-linked bond comes with a coupon of 0.375 percent which is multiplied by the index ratio. The index ratio is defined as the current inflation rate compared to the base index. In addition, the principal is adjusted upon redemption by multiplying the principal with the index ratio. At the same time, Orsted issued two other green bonds with a fixed-rate structure, running until 2027 and 2033. Both were priced with a higher coupon of 2.125% and 2.5%, respectively (Orsted, 2019). Similar to the Orsted bond, the coupon structure of the French bond follows a pre-defined interest amounting to 0.1% multiplied by an index ratio (French-Treasury, 2022). Thus, both green inflation bonds currently on the market are "c-linkers" using a national or European inflation index as a reference. To reflect reality and derive meaningful results, we model a green inflation-linked bond with a similar design as the above-described bonds meaning that it has a coupon which is multiplied by a selected inflation index (C-linker).

Table 1: Overview of selected green inflation-linked bonds - sources include Orsted (2019); Tresor (2022); Caproasia (2022)

Issuance date	Issuer	Issuance size	Coupon	Index
16.05.2019	Orsted	£ 250 M	0.375%	CPI
15.04.2022	Hongkong government	$ 1,900 M	0.375%	Local inflation
25.05.2022	France Treasury	€ 4,000 M	0.1%	HCPI

2.5. Convertible bonds

In mid-2021 the Economist pointed out the resurgence of convertible bonds by stating: "An asset class that had fallen out of fashion is back in vogue. That is because convertibles are well-suited to fast-changing conditions." (Economist, 2021). In its most basic form, convertible bonds are a debt-financing instrument that gives the investor the right to convert its debt into equity after a period of time or at maturity (Brennan and Schwartz, 1980; Ingersoll Jr, 1977; Dutordoir et al., 2014). Dutordoir et al. (2022) also point to the increased interest in convertible bonds in recent years after they have seen a lower demand in the aftermath of the financial crisis. Compared to fixed-rate bonds, inflation-linked, and other index-linked bonds, convertible bonds are issued solely by corporates. Similar to other bond classes, there are numerous different designs present in the market. Overall, convertible bonds can be differentiated along three main dimensions which are coupon paid (zero-coupon bonds vs. fixed-rate bonds), conversion right and obligation (issuer or investor can hold conversion right or obligation) and conversion timing (conversion can either be timed at maturity, at other pre-defined time, or at any time until maturity) (Choudhry, 2003). A key distinction between convertible bonds to other bond types is the pre-defined conversion price describing the price per share, for which the bond can be converted (Brennan and Schwartz, 1980, 1977; Dutordoir et al., 2014).

The main research stream deals with the pricing of convertible bonds. The complexity and research interest arise from the option-like structure which motivated the seminal work of Brennan and Schwartz (1977), Ingersoll Jr (1977), and Brennan and Schwartz (1980). Apart from the work on valuation models, scholars focused on the rationales for issuing convertible bonds, the market reaction to convertible bond issuance, and convertible bond design choices (Dutordoir et al., 2014). The key rationale for issuing convertible bonds is the reduction of both agency cost and adverse selection (e.g. Green, 1984; Mayers, 1998).

There is little research dedicated to green convertible bonds with only one paper by Lichtenberger et al. (2022) briefly discussing green convertible bonds. Irrespective of the lack of scholarly work, several green convertible bonds took place in recent months and years which are summarized in table 2. One of the largest green convertible bond offerings was issued in 2020 by EDF, a French utility company, amounting to € 2.4 bn and maturity until 2024. The structure follows a zero-coupon design and may be redeemed by EDF at certain times prior to the maturity (ISIN: FR0013534518) (EDF). In September 2022, NEOEN, a French renewable energy company, issued its second green convertible bond amounting to € 300 m and maturity in 2027. The bond pays a fixed coupon of 2.875% and can be redeemed by the company on any date after 2025 (ISIN: FR0013451820) (NEOEN, 2022). Hereafter, we use the structure of a plain vanilla convertible bond with a fixed coupon payment and investor's right for conversion at maturity. By doing so, we closely mirror the recent green convertible bond issuance of NEOEN and thus ensure a realistic setting (NEOEN, 2022).

Table 2: Overview of selected green convertible bonds - sources include LINK (2019); NEOEN (2022); NEOEN (2020); EDF; SP (2020); Audax (2020); Voltalia (2021); MeyerBurger (2021); Fisker (2021); POSCO (2021)

ISIN	Issuance date	Issuer	Issuance size	Coupon
HK0823032773	08.03.2019	LINK	$ 510 M	1.6%
-	27.05.2020	NEOEN	€ 170 M	2.0-2.5%
FR0010242511	14.09.2020	EDF	€ 2,400 M	0%
XS2234849649	16.09.2020	Falck Renewables	€ 200 M	0.0%
-	23.11.2020	Audax Renewables	€ 125 M	2.75%
-	05.01.2021	Voltalia	€ 200 M	1.0%
CH0108503795	05.07.2021	Meyer Burger	€ 125 M	2.75-3.25%
-	13.08.2021	Fisker	$ 625 M	2.5%
US6934831099	13.08.2021	POSCO	€ 1,100 M	0.0%
FR0011675362	07.09.2022	NEOEN	€ 300 M	2.875%

2.6. Carbon-linked bonds

Similar to inflation-linked bonds, carbon-linked bonds follow an index which is a carbon market such as the ETS. The first green carbon-linked bond emerged in 2008 shortly after the issuance of the first green bond itself (Worldbank, 2008a). Looking at the design of the first green carbon-linked bond, it initially offered a fixed-rate coupon which is superseded by a carbon-linked coupon after a 15-month period and had a relatively small issuance size of USD 25 M. This bond was jointly issued by the Worldbank and Daiwa and linked to the CER carbon price[4]. Apart from the carbon market itself, the coupon was also linked to the actual vs. estimated creation of CERs by a green project (hydro-power plant in China) (Worldbank, 2008a). Shortly after the first issuance, a second carbon-linked bond followed with a similar structure to the first one jointly issued by the Worldbank and Mitsubishi (Worldbank, 2008b). To the best of our knowledge, the carbon-linked bond issuance did not surge and only one additional carbon-linked bond was issued.[5] There are three potential reasons for this. Firstly, the issuance occurred in an early stage of the carbon market characterized by low(er) prices (Alberola et al., 2008). Hence, the bond might have fallen short of the return expectations by investors. Secondly, the bonds were linked to the development of CER prices which were important at the beginning and

[4] CERs stands for "Certified Emission Reductions" which are either issued by the Clean Development Mechanism (CDM) or the Joint Implementation Program (JI). They are generated as part of emission-reduction projects outside the EU and have been established as part of the Kyoto protocol. Similar to EUAs, one certificate accounts for 1 t of CO_2-equivalents (Nazifi, 2013; UN,2022)

lost importance with the development of ETS and other larger carbon markets. Finally, the bonds were not only linked to the carbon price development but the successful realization of a green project. As a result, they bear additional risks that investors might not be willing to accept.

Similarly, carbon-linked bonds have received relatively little attention from scholars. Bloch (2011) pioneers the field by deriving a pricing formula for carbon-linked bonds modeling both carbon price development and the projected vs. realized performance of the emission-reducing project. Following the initial idea of Bloch (2011), Zhang et al. (2020) present a carbon-linked bond design characterized by a double-barrier option. Using the upper and lower barrier, they show that when the carbon price increases, the issuer has to pay a lower coupon and vice versa (Zhang et al., 2020). A related field of research is commodity-linked bonds such as "petrobonds", which are linked to the development of oil prices (e.g. Schwartz, 1982; Carr, 1987). In our simulation, we combine the features of so-called "step-up/step-down" bonds[6] with a direct link to the development of the carbon market. Yet, we refrain from linking the coupon to the projected vs. actual performance of a project as a CER-generating project because of two reasons. Firstly, we would like to focus on one effect only which is the carbon price development to ensure that we obtain comparable results. Secondly, the CDM (Clean Development Mechanism) is based on the idea to generate CER as part of a green project which cannot be realized simultaneously with our proposed investment project.

Table 3: Overview of carbon-linked bond issuance - Sources include (Worldbank, 2008a, b; Reuters, 2014)

Issuance date	**Issuer**	**Issuance size**	**Coupon**	**Payment**
06.09.2008	World Bank and Daiwa	\$ 25 M	3%	Annual
09.12.2008	World Bank and Mitsubishi	\$ 6.5 M	3%	Annual
06.05.2014	CNG Wind	\$ 160 M	Not known	Not known

[6] As already reflected in the name, step-up or step-down bonds have an increasing or decreasing coupon structure which can be linked to a certain trigger or goal e.g. greenhouse gas emission reduction (Liberadzki et al., 2021; Berrada et al., 2022), to a rating (Koziol and Lawrenz, 2010) develops over time (ErsteGroup, 2014).

3. Model

3.1. Stochastic set-up

Our model has the objective to analyze whether different green bond structures improve the return and starting time of an emission-reducing project thus creating an incentive for the issuer to use a specific type of green bond. The chosen green bond types are a green fixed-rate bond which yields a constant interest until maturity, a green carbon-linked bond (with an up- and downward coupon structure), a green inflation-linked bond which yields a coupon adjusted for the underlying inflation level, and a green convertible bond with a fixed coupon structure and conversion dependent on the development of the underlying share price. The coupon payments for the different bond types and the investment project are based on three key processes which we need to define. Firstly, we need to define the development of CO_2 prices as both the carbon-linked bond and the investment project depend on it. Secondly, the inflation process needs to be detailed to model the inflation-linked bond. Finally, a process for the development of the share price needs to be drafted to calculate the convertible bond return.

We start by modeling the assumptions for the CO_2 price by defining the stochastic price P for the CO_2 certificates over time. In line with Bloch (2011) and Chevallier and Sévi (2014) we let P follow a geometric Brownian motion represented by the equation:

$$dP_t = \mu P_t dt + \sigma P_t d\widehat{W}_t \tag{3.1.}$$

where $t \geq 0$ and $P_0 := P(0)$. The two constants μ and σ stand for the drift rate and volatility of changes in the price of CO_2 certificates. The last component dW stands for the increment of a Wiener process on a filtered probability space $(\Omega, \mathcal{F}, \mathbb{P}, (\mathcal{F}_t)_{t\geq 0})$. As a next step, we define the price diffusion process for 3.1 under risk-neutral probability measure $\mathbb{Q}$. We can assume that CO_2 certificates are traded in a liquid public market (e.g. the ETS) and do not hold any storage yields. Thus, the risk associated to *P's* market price is described by λ_P and follows the properties of the Black and Scholes (1973) model expressed by $\lambda_P = \frac{\mu - r_f}{\sigma}$. r_f represents the risk-free rate. Finally, we can describe the price process with the following equation:

$$dP_t = r_f P_t dt + \sigma P_t dW_t \tag{3.2}$$

The above-described Wiener process is expressed by W_t. Note that assuming the dynamics of equation 3.2) come without loss of generality as other process adjustments reflecting idiosyncratic risks or storage yields are also possible. We assume that the constant μ is following a mean reverting process given by the following equation

$$d\mu_t = \kappa(\bar{\mu} - \mu_t)dt + \eta_t dz \tag{3.3}$$

whereas the mean reversion coefficient κ represents the adjustment speed for the rate of the growth process. μ_t illustrates the drift at time t which is assumed to follow the long-term average drift $\bar{\mu}$.

In order to receive the return of the convertible bond, we apply the share price *SP.* For the calculations, we assume the same conditions as for the carbon price P holds. Therefore, SP follows a geometric Brownian motion as well (see eq. 3.2).

Finally, the initially expected volatility of inflation is described by η_t, whereas z illustrates a random variable from a normal distribution.

Throughout the first section of this chapter, we assume the market prices follow a continuous time frame which reflects the properties of Black and Scholes (1973). For simulation, we transform equation (3.3) to the following discrete version (see e.g., Schwartz and Moon, 2000)

$$\mu_{t+\Delta t} = e^{-\kappa\Delta t}\mu_t + \left(1 - e^{-\kappa\Delta t}\right)\left(\bar{\mu} - \frac{\lambda\eta_t}{\kappa}\right) + \sqrt{\frac{1-e^{-2\kappa\Delta t}}{2\kappa}}\eta_t\sqrt{\Delta t z} \tag{3.4}$$

where λ represents the risk for the expected rate of growth and z illustrates in this case the standard random variable from a normal distribution again.

To calculate a system with multiple correlated variables, it is necessary to apply the Cholesky Decomposition. The objective of applying this procedure is to derive the correlation between the variables "carbon price", "inflation" and "share price". For that, it is necessary to start with a symmetric correlation matrix described by CM:

$$CM = \begin{pmatrix} 1 & \rho_{CP,HCPI} & \rho_{CP,SP} \\ \rho_{CP,HCPI} & 1 & \rho_{HCPI,SP} \\ \rho_{CP,SP} & \rho_{HCPI,SP} & 1 \end{pmatrix} \tag{3.5}$$

Where $\rho_{HCPI,SP}$ describes the correlation of inflation and share price, $\rho_{CP,HCPI}$ the correlation of inflation and carbon price, and $\rho_{CP,SP}$ the correlation of carbon and share price, respectively. Given the symmetric asset correlation CM, we can compute a lower diagonal matrix L by:

$$L = \begin{pmatrix} 1 & 0 & 0 \\ \rho_{CP,HCPI} & \sqrt{1-\rho_{CP,HCPI}^2} & 0 \\ \rho_{CP,SP} & \left(\frac{\rho_{HCPI,SP}-\rho_{CP,HCPI}\cdot\rho_{CP,SP}}{\sqrt{1-\rho_{CP,HCPI}^2}}\right) & \sqrt{1-\rho_{CP,SP}^2-\left(\frac{\rho_{HCPI,SP}-\rho_{CP,HCPI}\cdot\rho_{CP,SP}}{\sqrt{1-\rho_{CP,HCPI}^2}}\right)^2} \end{pmatrix} \tag{3.6}$$

The Cholesky Decomposition adjusts independent random variables X by using the lower diagonal matrix L to receive correlated variables $Z = LX$. Considered separately, Z creates in this case the correlated random variables:

$$Z = (\omega_1, \omega_2, \omega_3)^T \tag{3.7}$$

Where we define

$$\omega_1 = Z_1 \tag{3.8}$$

,

$$\omega_2 = \rho_{CP,HCPI} Z_1 + \sqrt{1 - \rho_{CP,HCPI}^2} Z_2 \tag{3.9}$$

as well as

$$\omega_3 = \rho_{CP,SP} \cdot Z_1 + \left(\frac{\rho_{HCPI,SP} - \rho_{CP,HCPI} \cdot \rho_{CP,SP}}{\sqrt{1 - \rho_{CP,HCPI}^2}} \right) Z_2 + \sqrt{1 - \rho_{CP,SP}^2 - \left(\frac{\rho_{HCPI,SP} - \rho_{CP,HCPI} \cdot \rho_{CP,SP}}{\sqrt{1 - \rho_{CP,HCPI}^2}} \right)^2} Z_3. \tag{3.10}$$

To conclude, we have defined the underlying processes of our model and how they are interrelated with each other. In the next two section we define the properties of the bond pricing and investment project.

3.2. Bond and coupon pricing

3.2.1. General note on pricing

Our project is assumed to be conducted by a firm that is partially debt-financed using different types of green bonds as financing instrument. As described above, we analyze a green fixed-rate bond, two green carbon-linked bonds, a green inflation-linked bond and a green convertible bond which are defined in the next sections. In order to specify the payoff structures of these bond types, we derive their general pricing equations. Before we define their individual properties, several principles can be outlined that are applicable for all bond types. We assume that the bonds have pre-determined time to maturity T_B and are redeemed at maturity. Moreover, they have face value FV and regular coupon payments $c_{(.)}$ that arise in every Δc-period. In addition to this, following assumptions applied in the model setup based on the framework of Ingersoll Jr (1977):

1. Bondholders have the preference to maximize their wealth.
2. Existence of perfect capital markets without any transaction costs or taxes.
3. All investors are informed equally and no existence of arbitrage.

4. Stockholders do not receive any dividends.
5. No existence of corporate taxes.

To make our model more comparable, all five bond types are priced on par at issuance, i.e., the fair present value $D_0 = FV$. To obtain D_0 of each bond we discount future payoffs under the measure $\mathbb{Q}$ with the risk-free rate r_f :

$$D_0 = \sum_{i=1}^{N=\frac{T_B}{\Delta t}} \frac{c_{(.),i} \cdot \Delta t \cdot FV}{\left(1+r_f\right)^{i \cdot \Delta t}} + \frac{FV}{(1+r_f)^{T_B}} \tag{3.11}$$

where $c_{(.),i}$ comprises the fixed and the carbon-linked coupons at any payment date. Note that to isolate the underlying incentive problem depicted by the bond types, we abstract from the risk of default, i.e. bondholders only face the risk of changing coupons.

Finally, we refrain from including default risk in the pricing equation as our model is focused on whether changing bond designs set different incentives to invest in emission-reducing project. This simplification gives us the ability to derive a concept rather than focus on individual default risk and thus focus on the key question of this paper.

3.2.2. Pricing of (green) fixed-rate bonds

The fixed-rate bond follows a simple structure of paying a constant coupon in each period which is denoted by c_{fix}. At maturity the bond is redeemed at a face value of $FV = 100$. This structure follows most of the green bonds currently in the market and is similar to the structure of many conventional bonds.

3.2.3. Pricing of (green) carbon-linked bond

The two carbon-linked bonds follow the idea of index-linked bonds such as inflation or commodity-linked bonds. In general, these bonds occur in two different designs: Either the principal payment is adjusted in dependence on the underlying index or the coupon payments may change. In this article, we analyze the latter type where the coupon function is linked to the absolute carbon price in incremental steps ("C-linker"). We chose an interval-based coupon structure which is inspired by step-up and step-down bonds applied in the conventional bond market as described by Koziol and Lawrenz (2010), to avoid large fluctuations due to relative changes in the carbon price from one year to another.

For the first carbon-linked bond, we assume that the coupons increase when the carbon prices increase. Thus, we denote coupons of that bond at any payment date i with

$$c_{up,i}=\begin{cases} c_{up,i}^{1}, P < y_1 \\ c_{up,i}^{2}, y_1 \leq P < y_2 \\ c_{up,i}^{3}, y_2 \leq P < y_3 \\ \vdots \end{cases} \tag{3.12}$$

where coupon levels satisfy $c_{up,i}^{1} < c_{up,i}^{2} < \cdots$ c2 and y_1, y_2 … describe critical coupon boundaries in ascending order. For the second carbon-linked bond, we assume an inverse relationship meaning that the coupons decrease when the carbon price increases.

$$c_{down,i}=\begin{cases} c_{down,i}^{1}, P < y_1 \\ c_{down,i}^{2}, y_1 \leq P < y_2 \\ c_{down,i}^{3}, y_2 \leq P < y_3 \\ \vdots \end{cases} \tag{3.13}$$

Thus, c_{down}, the bond's coupon payoff function, is congruent to Equation (3.5) but with $c_{down,i}^{1} > c_{down,i}^{2} \cdots$.

3.2.4. Pricing (green) inflation-linked bond

Next, we define the properties of the green inflation-linked bond. The coupon consists of two components: a constant interest rate cit_{IL} and an index ratio cir_{IL}. The constant rate is multiplied by the index ratio to account for the inflation adjustment. The index ratio follows the development of an inflation index inf. This index could be the Harmonized Consumer Price Index (HCPI) of the EU but other indices could be similarly applied. For the sake of simplicity, we assume that the index ratio is not subject to indexation lags which is the difference between the publication of inflation data and the time when it is reflected in the index ratio. In addition, we assume that each month has an equal amount of days and thus do not adjust the calculation accordingly. This gives us following formula for the applied index ratio cir_{IL}:

$$cir_{IL} = \frac{(inf_{cur} - inf_{iss}) + inf_{iss}}{inf_{iss}} \cdot 100 \tag{3.14}$$

where inf_{cur} stands for the current inflation rate (at time of coupon payment) and inf_{iss} denotes the inflation rate at issuance. Therefore, the formula for the coupon of the green inflation-linked bond takes the form:

$$c_{IL} = FV \cdot cit_{IL} \cdot cir_{IL} \tag{3.15}$$

where c_{IL} stands for the coupon payment of the green inflation-linked bond. At maturity, the redemption payment will be adjusted by inflation using the index ratio and yielding the equation:

$$re_{IL} = FV_{IL} \cdot cir_{IL} \tag{3.16}$$

The above-described design follows the structure of the bonds issued by Orsted (Orsted, 2019) and the French Treasury (French-Treasury, 2022) except for the simplification of indexation lags and days per month.

3.2.5. Pricing of (green) convertible bonds

As already illustrated in section 2.5., convertible bonds tend to appear ubiquitous in their hybrid nature because investors are able to trade the asset against the firm's stock, so that a direct exchange between debt and equity coexists (e.g. Xiao, 2013; Ballotta and Kyriakou 2015). The bond's structure is inspired by NEOEN (ISIN Code: FR0011675362). Unless the bondholder makes use of a previous conversion, the convertible bond can either be redeemed at par or converted at maturity T. To generate a model setup for convertible bonds, the following assumptions, following Ingersoll Jr (1977), are necessary:

1. All terms considering the conversion of the convertible bond remain constant over the whole time.
1. The bondholder needs to submit their claims for the conversion right after the convertible bond has been called.
2. As bondholders are willing to maximize wealth, the bond will be converted to stocks in case stocks are higher than the face value of the bond at maturity (t = T).
3. The stock price development follows a geometric Brownian Motion, so equation (3.1) holds.

For the underlying setup, we choose a convertible bond at time $t = 0$ with a maturity date of $T > 0$, a face value of $FV > 0$ which is solely repaid at maturity T. The chosen coupon has the amount of $c_{(.),i} > 0$, is paid at certain payment dates $t_i = \mathrm{i}\delta, where\ i = 1, 2, \ldots, N$ and where δ illustrates the time intervals between the coupons. For simplicity, we assume that all coupon payments are paid equally to the time interval δ. The bondholder is granted to exchange the bond into a predetermined number of $k > 0$ shares of the stock of the issuing firm after maturity T, whereas the element k denotes the number of shares that can be received at after the bond conversion. Contingent upon conversion, the bondholder obtains a certain conversion value
named CV of

$$CV = \frac{FV_c}{CP} \tag{3.17}$$

where FV_c describes the face value of the convertible and CP the conversion price.
According to Ingersoll Jr (1977),

$$\gamma \equiv \frac{n}{n+N} \tag{3.18}$$

illustrates the dilution factor γ which describes the fraction of the outstanding stocks N that can be exchanged by each investor for the amount of n which represents the amount of receivable convertible bonds. In case the value of the bond is lower than the conversion value, investors use the option to convert. To specify this option, we use the conversion condition by Brennan and Schwartz (1980) with the following equation

$$CV(V,r,t) \geq \gamma(V - nN(V,r,t)). \tag{3.19}$$

The market value of the firm is expressed by V, whereas CV describes the conversion value. CV is under dependence of the total firm value V and the current interest r at time t . CV needs to be greater or equal to the total shares of each convertible bond after conversion (γ). The convertible bond after conversion γresults from the subtraction of the current market value of the firm V and the number of outstanding convertible bonds n multiplied with the outstanding stocks N under the same condition as CV holds. Besides the NEOEN green convertible bond, especially the convertible market in the U.S. enables bondholders to give their bond back to the issuer at a certain amount and before the bond matures ($t = T$). This is often the face value plus interests (Kovalov and Linetsky, 2008). Albeit there are common conversion strategies, convertible bonds can vary in their execution. In the general setup, the issuer needs to announce the decision of the call during the call notice period. Is the convertible once called, the bondholder is required to decide whether the conversion option is exercised at the end of the call notice period, or if the call price will be directly received (Ballotta and Kyriakou, 2015). According to our example of the Neon convertible green bond, the bond can be redeemed at maturity T at the option of the company (NEOEN, 2022). In order to redeem the bond prior to maturity T, the call condition according to Brennan and Schwartz (1980) holds

$$CV(V,r,t) \leq CP(t) \tag{3.20}$$

where $CP(t)$ denotes the price of the convertible bond that is callable at time t. Therefore, if the callable price CP is larger or equal to the conversion value under dependencies of bond values V , r, and t, the call strategy becomes effective.

3.3. Impact on investment decision

In line with the green bond principles, the proceeds are invested in a climate-friendly project. The project has the objective to reduce CO_2 emissions and thus save CO_2 certificates which would otherwise have to be bought by the copay. We assume that there is no other financial return despite from saving CO_2 certificates. We have chosen this specific setup to analyze how different green bond structures encourage investors to finance emission-reducing projects. Further, we assume that the project is not at risk of not reaching the aspired reduction of CO_2 certificates (e.g., due to unforeseen technical difficulties). In addition to this, we do not implement a ramp up or construction phase in the project setting but assume that the CO_2 savings remain constant from the start of the project. To start the project, initial investments are required in the amount of the proceeds from the bond thus assuming $I_{\text{pro}} = FV$. In addition to the initial investment, operating cost amounting to C_{pro} are required in each period. As stated above, the return is solely driven by the carbon reduction and the reduction coincides with the investment. The project cannot be stopped after the initial investment and hence operating cost occur irrespective of the development of the carbon price. We define the number of saved CO_2 certificates as X and keep it constant in every Δt-periods over the lifetime of the project given by T_{pro}. As a result, the return is solely driven by the development of the carbon price in the market. We denote the payoffs of the project as CF and define j as the different points of time. Thus, the payoffs follow the form:

$$CF_{(.),j} = \begin{cases} X\left(P_j - C_{pro}\right) - c_{(.),j}FV, t_{pro} \leq j < T_B \\ X\left(P_j - C_{pro}\right) - (1 + c_{(.),j})FV, t_{pro} \leq j = T_B \\ X\left(P_j - C_{pro}\right), t_{pro} \leq T_B < j \leq t_{pro} + T_{pro} \end{cases} \tag{3.21}$$

To further simplify, we assume that before has been started cashflows equal to zero. Hence, we assume that the coupon payments are offset by reinvesting the bond proceeds at the market rate. Under the assumptions described above, the firm chooses an optimal starting point given the carbon price level. As a result, the described investment project follows a classic investment optimization problem. The firm chooses the boundary to maximize the Net Present Value (NPV) of the project and we denote it as $b^*_{(.)}$. This leaves us with the value maximizing function described by:

$$\max_{b^*_{(.)}} NPV_{pro,(.)} = \max_{b^*_{(.)}} \sum_{j=t_{pro}}^{M=t_{pro}+T_{pro}} \frac{CF_{(.),j}}{(1+r_f)^j} \tag{3.22}$$

Equation (3.22) states a classic optimal stopping time application, where $t_{\text{pro}} = \inf\{t \in [0, T_B]: P_t = b^*_{(.)}\}$.

4. Simulation-based implementation

After setting up the model, we specify the key parameters used in the simulation. To do so, table 4 lists the key parameters chosen and its respective levels for the first simulation. In addition, we have highlighted the parameters which are changed additional simulation to test the sensitivities.

Table 4: Parameter setting – Table shows key parameters for simulation and corresponding symbol. Column "(starting) value" represents the values chosen for the first simulation. Column "changed" shows which parameters are changed in subsequent simulations and which remain the same over all simulations

Parameter	**Symbol**	**(Starting) value**	**Changed**
Initial carbon price	P_0	20	
Risk-free rate	r_f	0.02	
Time to maturity of the bond	T_B	10	
Time to maturity of the project	T_P	10	
Time steps in simulation	Δ_t	1	
Project cost per Δ_t	c_{pro}	22	
Number of simulation paths	n	50,000	
Volatility of changes in carbon price	σ_{cp}	0.35	✓
Volatility of inflation	σ_i	0.1	✓
Volatility of share price	σ_{SP}	0.25	✓
Correlation of inflation and carbon price	$\rho_{CP,HCPI}$	0.23	✓
Correlation of inflation & share price	$\rho_{HCPI,SP}$	0.1	✓
Correlation of carbon price & share price	$\rho_{CP,SP}$	0.2	✓

We assume a carbon price is denoted by P_0 of 20 per certificate which reflects a price observed in the earlier days of the EU ETS system. As our model strives to derive a universally applicable method, we believe that the price of 20 is realistic despite a carbon price which is currently trading at higher levels. In addition to that, we set the risk-free rate to 2%. Both the bond and the project have maturity of ten periods (denoted by T_B and T_P respectively) and each time step in our simulation equals one. As outlined above, we assume that our project requires operating cost which amount to 22 per period and are denoted by c_{pro}. Our simulation generated n = 50,000 paths for the model. Our models underlying processes are based on carbon price, inflation and share price development. Thus, we need to define both the volatility of their individual development but also how they are correlated with each other. In the later part of this section we will present sensitivities of the model changing volatility and correlation. With the exemption of the correlation between carbon prices and inflation ($\rho_{CP,HCPI}$), all correlations and volatilities are not derived from historic data. Analyzing the historic European inflation data (HCPI) and carbon prices (EUA), we derive a correlation a value of $\rho_{CP,HCPI}$ = 0.23.

Before we can discuss the results of the model, we need to introduce the derived coupons for the different bond types. As mentioned above, we calibrated the bonds to have a face value of 100 and thus be comparable. Starting with the fixed rate, we assume a fixed coupon payment amounting to 2% until the time of maturity.

For the carbon-linked bond, we have introduced a structure similar to “step-up/step-down bonds”. We derive intervals by setting the number of step-ups/step-downs to n_{Steps} = 7. We set the difference between the two neighboring intervals to 1% − pt. and iteratively change c_1 to derive the required face value. Table 5 displays the resulting coupon structure.

Table 5: Carbon-linked bond coupon structure – Coupon levels applied in simulation depending on carbon price. Respective intervals calibrated to reach Face Value of 100.

Bond parameters	**Coupon for CP-linked up bond**	**Coupon for CP-linked down bond**
c_1 for p_{carb}< 10	0.0069	0.0331
c_2 for 10 ≤ p_{carb}< 25	0.0169	0.0231
c_3 for 25 ≤ p_{carb}< 40	0.0269	0.0131
c_4 for 40 ≤ p_{carb}< 55	0.0369	-0.0069
c_5 for 55 ≤ p_{carb}< 70	0.0469	-0.0069
c_6 for 70 ≤ p_{carb}< 85	0.0469	-0.0169
c_7 for p_{carb} ≥ 85	0.0569	-0.0269

The third bond structure we have introduced are green inflation-linked bonds. As described in section 3.2.3 we model a quasi-direct relationship to inflation. Thus, it is not possible to illustrate a similar table with coupon structures for inflation-linked bonds. Still, as described in the formula $c_{IL} = FV \cdot cit_{IL} \cdot cir_{IL}$, the coupon payment of the inflation-linked bond is based on a fixed coupon multiplied with an index that changes according to the inflation. Applying the same logic as for the carbon-linked bonds, we calibrate cit_{IL} to generate a face value equal 100. This yields us $cit_{IL} = 0.01411$.

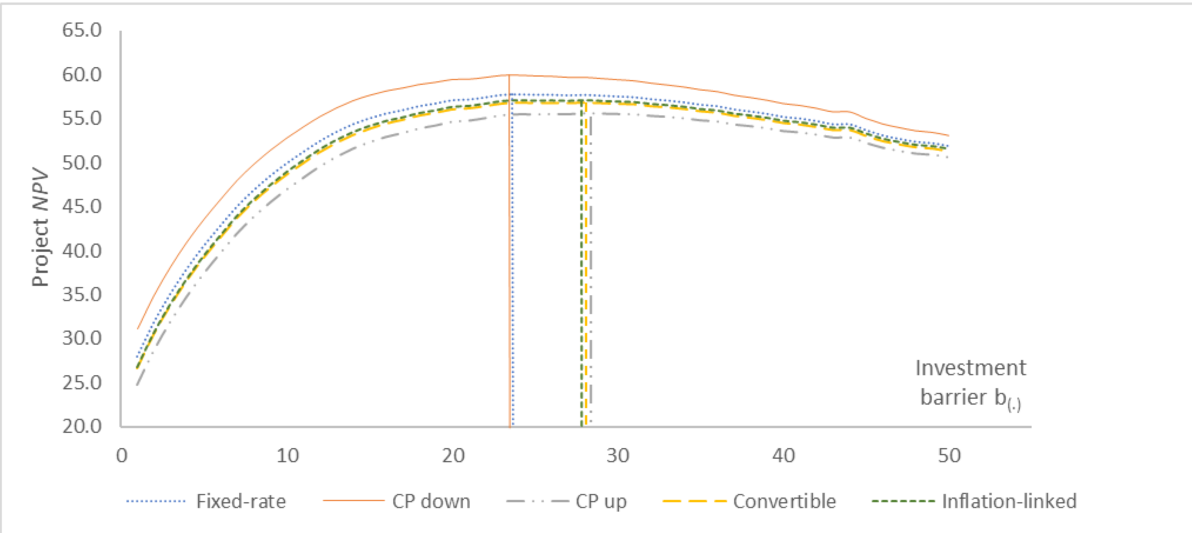
Finally, to generate the coupon payment of the green convertible bond, we apply the same procedure which yields a coupon of $c_{CON} = 0.01279$.

As outlined above, we compare the NPV and barrier of the different bonds to analyze their performance. Our results indicate that only the green carbon-linked bond with an inversed coupon structure compared to the carbon price development outperforms the green fixed rate bonds. The green-carbon linked bond reaches an NPV of 59.96 which is 3.8% or 2.21 points higher than the green-fixed rate bond. In addition to this, the project is started at a carbon price level of 24 both for the green-fixed rate bond and the green carbon-linked down bond.

Table 6: Results – The table depicts the simulation results based on the specifications in table 4. The volatility of changes in carbon price (σ), correlation of inflation and carbon price (ρ), optimal barrier $b_{(.)}$, and corresponding NPV for both financing choices under changing volatility. All other parameters as defined in Table 4.

Green fixed bond		**Green CP-linked up bond**		**Green CP-linked down bond**		**Green inflation-linked Bond**		**Green convertible bond**	
NPV	**Barrier**	**NPV**	**Barrier**	**NPV**	**Barrier**	**NPV**	**Barrier**	**NPV**	**Barrier**
57.75	24	55.66	28	59.96	24	57.11	28	56.82	28

Figure 1: Results – Graph shows the NPV on the y-axis and investment barrier on the x-axis. All five bonds designs are illustrated here comprising the curved lines. The straight lines from the curve to the x-axis should illustrate the investment barrier. There are only two investment barrier which are 24 and 28 in our results. In order to increase the readability of the graph we have slightly staggered the lines but they are at the same point (either 24 or 28).



The results are illustrated in figure 1 which shows that the green carbon-linked down bond has the highest NPV and the lowest investment barrier. The green fixed-rate bond comes with the same investment barrier but with a lower NPV. All other bond designs have an investment barrier of 28 and slightly different NPVs that are all lower than the green carbon-linked down bond and the green fixed-rate bond.

In order to interpret the results, we recall our initial research objective which is to investigate whether there are green bond designs that set incentives for a firm to implement emission-reducing projects.

As stated above, the results of the model indicate that the green carbon-linked bond with an inversed coupon structure yields the highest NPV. Still, before concluding about whether it sets the right incentives, we need to discuss what the design implies for both the issuer (firm invests in the emission-reducing project) and the investor which buys the green bond from the issuer. From an issuer point of view, the selection of the green carbon-linked down bond has the implication that it would end up paying lower coupons to the investor as the carbon price increases. Thus, the incentive alignment is fulfilled, and the issuer enjoys two benefits.

Firstly, it lowers the funding cost when the carbon price increases. Secondly, it does not suffer from the increased carbon price regarding the need to buy (expensive) CO_2 certificates, but saves (partly) the certificates due to the emission-reducing project. Assuming that the investor also has the objective to contribute to the reduction of carbon emission, it would accept a lower coupon when carbon prices are increasing in exchange for reduction of CO_2 emissions. Summarizing, the green carbon-linked bond with an inversed coupon structure could be a design to promote the reduction of CO_2 emissions by aligning the incentives of both issuer and investor. Coming back to the idea of putting a price on carbon which is to price the "social cost" of carbon, one can argue that an increasing carbon price signals increasing social cost and thus more pressing need to reduce carbon emissions which would be incentivized with the setting above.

In order to test the results of the first specification of the model, we run several sensitivity analyses. The modified variables in this analysis are volatility σ and correlation ρ. For this, we change the values for the volatility of the carbon price σ_{cp}, the volatility of inflation σ_i as well as the volatility of share price σ_{SP}. Together with the volatilities, we add the correlations of inflation and carbon price $\rho_{\mathrm{CP,HCPI}}$, the correlation of inflation and share price $\rho_{HCPI,SP}$ as well as the correlation of carbon and share price $\rho_{CP,SP}$ (see table 7). Before we come to the results, we briefly explain the applied changes in the parameters of the model. In the first three sensitivities we stick to the volatilities of the original setting and only change the correlations. In the second sensitivity, we reduce the correlations of all three combinations. In the third sensitivity, we increase the correlation of inflation and carbon ($\rho_{\mathrm{CP,HCPI}}$) as well as the correlation of carbon and share prices ($\rho_{CP,SP}$). Moreover, we assume that the inflation and share price have a negative correlation ($\rho_{HCPI,SP}$). In the third sensitivity, we increase the correlation of inflation and carbon price ($\rho_{HCPI,SP}$) while keeping the rest almost constant. In the final two sensitivities we assume that the correlations take the value of the original setting and only change the volatilities. In the fourth sensitivity, we decrease the volatility of all three processes. Finally, in the last sensitivity, we again slightly increase the volatilities of all three processes but keep it below the original setting. While the NPVs fluctuate along the different sensitivities, the results of the original setting are confirmed which is that the carbon-linked down bond yields the highest NPV followed by the fixed-rate bond. This holds for all applied sensitives and is shown in table 7.

	Volatility			Correlation			Fixed rate		CP-linked up		CP-linked down		Inflation - linked		Convertible	
Model version	σ_{cp}	σ_i	σ_{SP}	$\rho_{CP,HCPI}$	$\rho_{HCPI,SP}$	$\rho_{CP,SP}$	**NPV**	**BR**	**NPV**	**BR**	**NPV**	**BR**	**NPV**	**BR**	**NPV**	**BR**
Original	0.35	0.1	0.25	0.23	0.1	0.2	57.75	24	55.66	28	59.96	24	57.11	28	56.82	28
Sensi 1	0.35	0.1	0.25	0.1	0.05	0.05	59.90	24	57.71	25	62.10	24	59.55	24	59.02	24
Sensi 2	0.35	0.1	0.25	0.3	-0.05	0.15	58.30	24	56.16	27	60.50	24	57.44	27	57.11	27
Sensi 3	0.35	0.1	0.25	0.4	-0.1	0.1	59.35	28	57.32	28	61.38	28	58.35	28	58.48	28
Sensi 4	0.15	0.05	0.15	0.23	0.1	0.2	16.59	9	15.78	9	17.42	8	15.64	10	16.33	9
Sensi 5	0.25	0.25	0.25	0.23	0.1	0.2	38.87	18	37.31	18	40.49	16	37.63	18	37.88	18

Table 7: Sensitivities - Table shows the results of the simulation using different specifications. Volatility of changes in carbon price (σ_{cp}), inflation (σ_i) and share price (σ_{SP}) are modified. Furthermore, correlation of inflation and carbon price ($\rho_{CP,HCPI}$), inflation and share price ($\rho_{HCPI,SP}$) and share price and carbon price ($\rho_{CP,SP}$) are adjusted. Original version corresponds to specification and results as in table 6. *BR* stands for the barrier (carbon price level).

5. Conclusion

Using a simulation-based approach, we have analyzed whether different green designs set superior incentives to invest in emission-reducing projects. To do so, we have examined five different green bond designs from traditional fixed-rate bonds to convertible bonds. We understand the incentive as the resulting NPV of the project and assume that the issuer would choose the bond leading to the highest NPV. In addition, the starting time of the project tells us which bond is the best suited to accelerate investments in emission-reducing projects. Thus, our analysis helps to understand whether there are specific bond designs that might be used as (more) effective debt-financing instruments to narrow the financing gap in fighting climate change. To the best of our knowledge, it is the first paper evaluating the return of an emission-reducing project financed by green bonds.

Our analysis holds various important implications for bond issuers in general, policy recommendations to finance actions against climate change, and for future research.

Our key finding is that most complex green bond designs do not set superior incentives compared to the traditional fixed-rated bond design. We have discovered one exemption here which are green carbon-linked bonds with inversed coupon structure compared to the carbon price development.

This finding is remarkable due to two reasons. First, green carbon-linked bonds have not seen a surge compared to other green bond types such as the fixed-rated or convertible green bonds. Thus, we see potential to revitalize the market for this specific bond design. Secondly, our finding questions the use of complex bond designs such as green inflation-linked or green convertible bonds. If their more complex structures do not set better incentives, there has to be other reasons for their issuance beyond our analysis framework.

For a policy perspective, our findings question whether complex green bond designs should be promoted by supranational institutions, governments and initiatives such as the Climate Bond Initiative as they do not set superior incentives compared to less complex fixed-rate bonds. Still, our research could motivate institutions such as the World Bank to reboot the issuance of carbon-linked bonds and take the role of a market-maker similar to the first issuances in 2007 and 2008.

Finally, our paper strives to develop a framework to evaluate different bond structures. We hope that it is used by other scholars to evaluate different bond designs to find (more) efficient structures to narrow the financing gap. In addition, we believe that it lays the groundwork for future research paths described in the later section.

Our findings do not come without limitations. In our simulation, we have modeled carbon price and inflation along assumptions about their development (i.e. mean reverting process for inflation). Issuers might operate under different assumptions e.g., predicting a different inflation environment making the inflation-linked bond more attractive. In addition, we have omitted the default risk as we are interested in the incentivization function only. Still, in a real bond issuance default risk needs to be included to derive the fair value.

One of the most controversial topics around green bonds is the so-called greenium. As of today, there are no conclusive answers and thus we have not included it in the model. Finally, it is important to mention that we have replicated the bond design of green bonds that are currently at the market. While we believe that this provides us with relevant answers, there might be alternative bond designs that yield other results than the ones presented here. Still, issuers might use inflation-linked bonds to pursue other purposes which we have not covered here in detail. From the issuer's point of view, one might use inflation-linked bonds as an alternative investment for specific investors. This might also lead to lower financing costs in case the demand for inflation-linked bonds is significantly higher than the issuance volume. Furthermore, issuers might want to link their interest payment to inflation in order to balance their overall debt service. Similarly, investors in the bond market might use this to diversify their portfolio and to hedge against risk of unexpected inflation.

This opens several routes for future research. First, one could investigate whether the hypothesis holds that green inflation-linked and green convertible bonds attract different type of investors compared to fixed-rate bonds. In addition, one might apply a qualitative research approach (e.g., structured interviews) to understand the rationales for investor and issuers. Moreover, empirical research on the drivers of bond demand could help to better understand the preference of investors and thus optimize bond structures. In the same vein, scholars might investigate the potential carbon-linked bonds in terms of portfolio allocation and diversification. As stated above, we see our model as a framework to evaluate other bond designs and, thus, stimulate scholars to apply it to other structures, e.g., zero-coupon or commodity-linked bonds.

References

Alberola, E., Chevallier, J., 2009. European carbon prices and banking restrictions: Evidence from phase i (2005-2007). The Energy Journal 30.

Alberola, E., Chevallier, J., Chèze, B., 2008. Price drivers and structural breaks in european carbon prices 2005–2007. Energy policy 36, 787–797.

Albul, B., Jaffee, D.M., Tchistyi, A., 2015. Contingent convertible bonds and capital structure decisions. Available at SSRN 2772612.

Andersson, J., et al., 2015. Cars, carbon taxes and CO2 emissions. Grantham Research Institute on Climate Change and the Environment.

Arif, M., Naeem, M.A., Farid, S., Nepal, R., Jamasb, T., 2022. Diversifier or more? hedge and safe haven properties of green bonds during covid-19. Energy Policy 168, 113102.

Audax, 2020. Audax launches its first green bond. URL: https://www.audaxrenovables.com/en/ndp-audax_emision-bonos-internacionales/. Last accessed 5 November 2022.

Auer, H., Crespo del Granado, P., Oei, P.Y., Hainsch, K., Löffler, K., Burandt, T., Huppmann, D., Grabaak, I., 2020. Development and modelling of different decarbonization scenarios of the European energy system until 2050 as a contribution to achieving the ambitious 1.5 °C climate target-establishment of open source/data modelling in the European H2020 project openENTRANCE. e & I Elektrotechnik und Informationstechnik, 137(7), 346–358.

Bachelet, M.J., Becchetti, L., Manfredonia, S., 2019. The green bonds premium puzzle: The role of issuer characteristics and third-party verification. Sustainability 11, 1098.

Baker, M., Bergstresser, D., Serafeim, G., Wurgler, J., 2018. Financing the response to climate change: The pricing and ownership of US green bonds. Technical Report. National Bureau of Economic Research.

Ballotta, L., Kyriakou, I., 2015. Convertible bond valuation in a jump diffusion setting with stochastic interest rates. Quantitative Finance 15, 115–129.

Banga, J., 2019. The green bond market: a potential source of climate finance for developing countries. Journal of Sustainable Finance & Investment 9, 17–32.

Bardong, F., Lehnert, T., 2004. Tips, break-even inflation, and inflation forecasts. The Journal of Fixed Income 14, 15–35.

Beck, U., Kruse-Andersen, P.K., 2020. Endogenizing the cap in a cap-and-trade system: Assessing the agreement on eu ets phase 4. Environmental and Resource Economics 77, 781–811.

Benz, E., Trück, S., 2009. Modeling the price dynamics of co2 emission allowances. Energy Economics 31, 4–15.

Black, F., Scholes, M., 1973. The pricing of options and corporate liabilities. The Journal of Political Economy 81, 637–654.

Bloch, D.A., 2011. The pricing of carbon bonds and other index-linked carbon derivatives. Available at SSRN 1763168.

Bloomberg, 2022. EU ets 2021 review – big carbon is here to stay: Bnef. URL: https://www.bloomberg.com/press-releases/2021-12-15/eu-ets-2021-review-big-carbon-is-here-to-stay-bnef. last accessed 2 October 2022.

Bodie, Z., 1988. Inflation, index-linked bonds, and asset allocation.

Boermans, M.A., Van Wijnbergen, S., 2018. Contingent convertible bonds: Who invests in european cocos? Applied Economics Letters 25, 234–238.

Boyce, J.K., 2018. Carbon pricing: effectiveness and equity. Ecological Economics 150, 52–61.

Brennan, M.J., Schwartz, E.S., 1977. Convertible bonds: Valuation and optimal strategies for call and conversion. The Journal of Finance 32, 1699–1715.

Brennan, M.J., Schwartz, E.S., 1980. Analyzing convertible bonds. Journal of Financial and Quantitative analysis 15, 907–929.

Broadstock, D.C., Cheng, L.T., 2019. Time-varying relation between black and green bond price benchmarks: Macroeconomic determinants for the first decade. Finance research letters 29, 17–22.

Caldara, D., Conlisk, S., Iacoviello, M., Penn, M., 2022. The Effect of the War in Ukraine on Global Activity and Inflation.

Campbell, J.Y., Shiller, R.J., Viceira, L.M., 2009. Understanding inflation-indexed bond markets. Technical Report. National Bureau of Economic Research.

Caproasia, 2022. Hong kong government relaunch $ 1.9 billion 3-year inflation-linked retail green bond at minimum 2.5%. URL: https://www.caproasia.com/2022/04/15/ hong-kong-government-issues-1-9-billion-3-year-inflation-linked-retail-green-bond-last accessed 5 November 2022.

Carr, P., 1987. A note on the pricing of commodity-linked bonds. The Journal of Finance 42, 1071–1076.

Chevallier, J., Sévi, B., 2014. On the stochastic properties of carbon futures prices. Environmental and Resource Economics 58, 127–153.

Choudhry, M., 2003. Bond and money markets: strategy, trading, analysis. Butterworth-Heinemann.

Choudhry, M., 2010. An introduction to bond markets. John Wiley & Sons.

Choudhry, M., Joannas, D., Pereira, R., Pienaar, R., 2005. Inflation-indexed bonds and derivatives, in: Capital Market Instruments. Springer, pp. 191–213.

Christiansen, A.C., Arvanitakis, A., Tangen, K., Hasselknippe, H., 2005. Price determinants in the eu emissions trading scheme. Climate Policy 5, 15–30. Climate-Policy-Initiative, 2021. Global landscape of climate finance 2021. URL: https://www.climatepolicyinitiative.org/publication/global-landscape-of-climate-finance-2021/. last accessed 1 October 2022.

Creti, A., Jouvet, P.A., Mignon, V., 2012. Carbon price drivers: Phase i versus phase ii equilibrium? Energy Economics 34, 327–334.

Danish-National-Bank, 2022. Inflation-linked bonds. URL: https://www.nationalbanken.dk/en/governmentdebt/IR/Pages/Inflation-linked-Bond.aspx. last accessed 1 October 2022.

Den Elzen, M.G., Hof, A.F., Beltran, A.M., Grassi, G., Roelfsema, M., van Ruijven, B., van Vliet, J., van Vuuren, D.P., 2011. The Copenhagen Accord: abatement costs and carbon prices resulting from the submissions. environmental science & policy 14, 28–39.

Dorfleitner, G., Utz, S., Zhang, R., 2022. The pricing of green bonds: external reviews and the shades of green. Review of Managerial Science 16, 797–834.

Dutordoir, M., Lewis, C., Seward, J., Veld, C., 2014. What we do and do not know about convertible bond financing. Journal of Corporate Finance 24, 3–20.

EDF. Edf announces the success of its inaugural landmark offering of green bonds convertible into new shares and/or exchangeable for existing shares (oceanes vertes), year = 2020, note = Last accessed 15

October 2022, url = https://www.edf.fr/en/the-edf-group/dedicated-sections/journalists/allpress-releases/edf-announces-the-success-of-its-inaugural-landmark-offering-ofgreen-bonds-convertible-into-new-shares-and-or-exchangeable-for-existing-sharesoceanes-vertes.

EIB, 2022. Climate awareness bonds. URL: https://www.eib.org/en/investor-relations/cab/index.htm. last accessed 1 October 2022.

ErsteGroup, 2014. Erste group subordinated step-up coupon note 2014-2022. URL: https://produkte.erstegroup.com/Retail/en/Products/Bonds/Factsheets/Bond_General/index.phtml?ID_NOTATION=102412760&ISIN=AT0000A17J78. last accessed 15 October 2022.

European Commission, 2016. Study on the potential of green bond finance for resource-efficient investments. URL: https://ec.europa.eu/environment/enveco/pdf/potential-green-bond.pdf. last accessed 1 October 2022.

European Commission, 2022. Eu emissions trading system. URL: https://climate.ec.europa.eu/eu-action/eu-emissions-trading-system-eu-ets_en#a-cap-and-trade-system. last accessed 1 October 2022.

Eurostat, 2022. Glossary:carbon dioxide equivalent. URL: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Glossary:Carbon_dioxide_equivalent#:~:text=A%20carbon%20dioxide%20equivalent%20or,with%20the%20same%20global%20warming. last accessed 2 October 2022.

Fankhauser, S., Sahni, A., Savvas, A., Ward, J., 2016. Where are the gaps in climate finance? Climate and Development 8, 203–206.

Ferrer, R., Shahzad, S.J.H., Soriano, P., 2021. Are green bonds a different asset class? evidence from time-frequency connectedness analysis. Journal of Cleaner Production 292, 125988.

Fisker, 2021. Fisker inc. announces upsize and pricing of $ 625,000,000 green convertible notes offering. URL: https://investors.fiskerinc.com/news/news-details/2021/Fisker-Inc.-Announces-Upsize-and-Pricing-of-625000000-Green-Convertible-Notes-Offering/default.aspx. last accessed 5 November 2022.

Flaherty, M., Gevorkyan, A., Radpour, S., Semmler, W., 2017. Financing climate policies through climate bonds–a three stage model and empirics. Research in International Business and Finance 42, 468–479.

Flammer, C., 2020. Green bonds: effectiveness and implications for public policy. Environmental and Energy Policy and the Economy 1, 95–128.

Flammer, C., 2021. Corporate green bonds. Journal of Financial Economics 142, 499–516.

Fleckenstein, M., Longstaff, F.A., Lustig, H., 2014. The tips-treasury bond puzzle. the Journal of Finance 69, 2151–2197.

French-Treasury, 2022. Green oati 0.10 % 25 july 2038. URL: https://www.aft.gouv.fr/en/titre/fr001400aqh0. last accessed 2 October 2022.

Garcia, J.A., van Rixtel, A.A., 2007. Inflation-linked bonds from a central bank perspective. ECB Occasional Paper.

Green, R.C., 1984. Investment incentives, debt, and warrants. Journal of financial Economics 13, 115–136.

Hachenberg, B., Schiereck, D., 2018. Are green bonds priced differently from conventional bonds? Journal of Asset Management 19, 371–383.

Hammond, P.B., 2002. Understanding and using inflation bonds. TIAA-CREF Research Dialogue 73.

Han, Y., Li, J., 2022. Should investors include green bonds in their portfolios? Evidence for the USA and Europe. International Review of Financial Analysis 80, 101998.

Hao, Y., Tian, C., Wu, C., 2020. Modelling of carbon price in two real carbon trading markets. Journal of Cleaner Production 244, 118556.

Heine, D., Semmler, W., Mazzucato, M., Braga, J.P., Gevorkyan, A., Hayde, E.K., Radpour, S., 2019. Financing low-carbon transitions through carbon pricing and green bonds. World Bank Policy Research Working Paper.

Hintermann, B., 2010. Allowance price drivers in the first phase of the eu ets. Journal of Environmental Economics and Management 59, 43–56.

Hojnik, J., Ruzzier, M., Fabri, S., Klopcic, A.L., 2021. What you give is what you get: Willingness to pay for green energy. Renewable Energy 174, 733–746.

Hong, H., Karolyi, G.A., Scheinkman, J.A., 2020. Climate finance. The Review of Financial Studies 33, 1011–1023.

Hyun, S., Park, D., Tian, S., 2019. Differences between green bonds versus conventional bonds: An empirical exploration. Handbook of green finance, sustainable development. Springer, Singapore, 91–134.

Ibikunle, G., Gregoriou, A., Hoepner, A.G., Rhodes, M., 2016. Liquidity and market efficiency in the world's largest carbon market. The British Accounting Review 48, 431–447.

ICMA, 2022. Green bond principles (gbp). URL: https://www.icmagroup.org/sustainable-finance/the-principles-guidelines-and-handbooks/green-bond-principles-gbp/. last accessed 2 October 2022.

IEA, 2021. World energy outlook 2021. URL: https://iea.blob.core.windows.net/assets/4ed140c1-c3f3-4fd9-acae-789a4e14a23c/WorldEnergyOutlook2021.pdf. last accessed 1 October 2022.

IEA, 2022a. South african carbon tax. URL: https://www.iea.org/policies/3041-south-african-carbon-tax. last accessed 2 October 2022.

IEA, 2022b. World energy outlook 2022. URL: https://www.iea.org/reports/world-energy-outlook-2022. last accessed 5 November 2022.

IEA2022, 2022. World energy investment 2022. URL: https://www.iea.org/reports/world-energy-investment-2022/overview-and-key-findings. last accessed 1 October 2022.

Immel, M., Hachenberg, B., Kiesel, F., Schiereck, D., 2021. Green bonds: Shades of green and brown. Journal of asset management 22, 96–109.

Ingersoll Jr, J.E., 1977. A contingent-claims valuation of convertible securities. Journal of Financial Economics 4, 289–321.

Jarrow, R., Yildirim, Y., 2003. Pricing treasury inflation protected securities and related derivatives using an hjm model. Journal of Financial and Quantitative Analysis 38, 337–358.

Ji, L., Zou, Y., He, K., Zhu, B., 2019. Carbon futures price forecasting based with arima-cnn-lstm model. Procedia Computer Science 162, 33–38.

Kaminker, C., Stewart, F., 2012. The role of institutional investors in financing clean energy.

Karpf, A., Mandel, A., 2017. Does it pay to be green? Available at SSRN 2923484.

Kaufman, N., Barron, A.R., Krawczyk, W., Marsters, P., McJeon, H., 2020. A near-term to net zero alternative to the social cost of carbon for setting carbon prices. Nature Climate Change 10, 1010–1014.

Klenert, D., Mattauch, L., Combet, E., Edenhofer, O., Hepburn, C., Rafaty, R.,Stern, N., 2018. Making carbon pricing work for citizens. Nature Climate Change 8, 669–677.

Kothari, S., Shanken, J., 2004. Asset allocation with inflation-protected bonds. Financial Analysts Journal 60, 54–70.

Kovalov, P., Linetsky, V., 2008. Valuing convertible bonds with stock price, volatility, interest rate, and default risk. FDIC Center for Financial Research Working Paper Series .

Koziol, C., Lawrenz, J., 2010. Optimal design of rating-trigger step-up bonds: Agency conflicts versus asymmetric information. Journal of Corporate Finance 16, 182–204.

Lamphiere, M., Blackledge, J., Kearney, D., 2021. Carbon futures trading and short-term price prediction: An analysis using the fractal market hypothesis and evolutionary computing. Mathematics 9, 1005.

Larcker, D.F., Watts, E.M., 2020. Where's the greenium? Journal of Accounting and Economics 69, 101312.

Li, G., Ning, Z., Yang, H., Gao, L., 2022. A new carbon price prediction model. Energy 239, 122324.

Liberadzki, M., Jaworski, P., Liberadzki, K., 2021. Spread analysis of the sustainability-linked bonds tied to an issuer's greenhouse gases emissions reduction target. Energies 14, 7918.

Lichtenberger, A., Braga, J.P., Semmler, W., 2022. Green bonds for the transition to a low-carbon economy. Econometrics 10, 11.

LINK, 2019. Link issues green convertible bond - a first for real estate sector worldwide. URL: https://www.linkreit.com/en/sustainability/case-studies/link-issues-green-convertible-bond-a-first-for-real-estate-sector-worldwide/. last accessed 5 November 2022.

Löffler, K.U., Petreski, A., Stephan, A., 2021. Drivers of green bond issuance and new evidence on the "greenium". Eurasian Economic Review 11, 1–24.

Maltais, A., Nykvist, B., 2020. Understanding the role of green bonds in advancing sustainability. Journal of Sustainable Finance & Investment , 1–20.

Mansanet-Bataller, M., Pardo, A., Valor, E., 2007. Co2 prices, energy and weather. The Energy Journal 28.

Mayers, D., 1998. Why firms issue convertible bonds: the matching of financial and real investment options. Journal of financial economics 47, 83–102.

McCollum, D.L., Zhou, W., Bertram, C., De Boer, H.S., Bosetti, V., Busch, S., Despr´es, J., Drouet, L., Emmerling, J., Fay, M., et al., 2018. Energy investment needs for fulfilling the paris agreement and achieving the sustainable development goals. Nature Energy 3, 589–599.

Mercurio, F., Moreni, N., 2006. Inflation with a smile. Risk 19, 70–75.

MeyerBurger, 2021. Meyer burger technology launches private placement. URL: https://www.meyerburger.com/pl/newsroom/artikel/meyer-burger-technology-launches-private-placement-of-up-to-160-mn-new-shares-and last accessed 5 November 2022.

Mintz-Woo, K., Dennig, F., Liu, H., Schinko, T., 2021. Carbon pricing and covid-19. Climate Policy 21, 1272–1280.

Murray, B., Rivers, N., 2015. British columbia's revenue-neutral carbon tax: A review of the latest "grand experiment" in environmental policy. Energy Policy 86, 674–683.

Nazifi, F., 2013. Modelling the price spread between eua and cer carbon prices. Energy Policy 56, 434–445.

NEOEN, 2020. NEOEN launches the first ever european green convertible bond issue for a maximal nominal amount of €170million.URL : . last accessed 5 November 2022.

NEOEN, 2022. NEOEN announces the success of its offering of green bonds convertible into new shares and/or exchangeable for existing shares due 2027 for a nominal amount of € 300 million. https://neoen.com/en/news/2022/neoen-announces-the-success-of-its-offering-of-green-bonds-convertible-into-new-shares. last accessed 15 October 2022.

Ng, T.H., Tao, J.Y., 2016. Bond financing for renewable energy in asia. Energy Policy 95, 509–517.

Ning, Y., Cherian, J., Sial, M.S., Álvarez-Otero, S., Comite, U., Zia-Ud-Din, M., 2022. Green bond as a new determinant of sustainable green financing, energy

efficiency investment, and economic growth: a global perspective. Environmental Science and Pollution Research , 1–16.

Nogrady, B., et al., 2021. China launches world's largest carbon market: but is it ambitious enough? Nature 595, 637–637.

Nordeng, A., 2022. Carbon trading: exponential growth on record high. https://www.refinitiv.com/perspectives/market-insights/carbon-trading-exponential-growth-on-record-high/. last accessed 1 October 2022.

Nordhaus, W., 2019. Climate change: The ultimate challenge for economics. American Economic Review 109, 1991–2014.

OECD, 2021. Scaling up green, social, sustainability and sustainability-linked bond issuances in developing countries. https://www.oecd.org/officialdocuments/publicdisplaydocumentpdf/?cote=DCD(2021)20&docLanguage=En. last accessed 1 October 2022.

OECD, 2020. Global Outlook on Financing for Sustainable Development 2021. https://www.oecd.org/dac/global-outlook-on-financing-for-sustainable-development-2021-e3c30a9a-en.htm Last accessed 05 November 2022.

Orsted, 2019. Ørsted successfully issues green bonds. https://orsted.com/en/company-announcement-list/2019/05/1821058. last accessed 2 October 2022.

Oster, P., 2020. Contingent convertible bond literature review: making everything and nothing possible? Journal of Banking Regulation 21, 343–381.

Park, J., 2022. How can we pay for it all? understanding the global challenge of financing climate change and sustainable development solutions. Journal of Environmental Studies and Sciences 12, 91–99.

Park, S.K., 2018. Investors as regulators: Green bonds and the governance challenges of the sustainable finance revolution. Stan. J. Int'l L. 54, 1.

POSCO, 2021. Posco raises €1.1 bn in convertible green bonds. https://www.kedglobal.com/corporate-bonds/newsView/ked202108150003. last accessed 5 November 2022.

Price, M.R.T., 1997. The rationale and design of inflation-indexed bonds .

Reboredo, J.C., 2018. Green bond and financial markets: Co-movement, diversification and price spillover effects. Energy Economics 74, 38–50.

Reboredo, J.C., Ugolini, A., 2020. Price connectedness between green bond and financial markets. Economic Modelling 88, 25–38.

Reschreiter, A., 2004. Conditional funding costs of inflation-indexed and conventional government bonds. Journal of Banking & Finance 28, 1299–1318.

Reuters, 2014. China to launch first carbon-linked financial product on thursday. https://www.reuters.com/article/china-carbon-idUSL3N0NS0FI20140506. last accessed 5 November 2022.

Reuters, 2022a. Carbon needs to cost at least $ 100/tonne now to reach net zero by 2050: Reuters poll. https://www.reuters.com/business/cop/carbon-needs-cost-least-100tonne-now-reach-net-zero-by-2050-2021-10-25/ last accessed 5 November 2022.

Roberts, J.T., Weikmans, R., Robinson, S.a., Ciplet, D., Khan, M., Falzon, D., 2021. Rebooting a failed promise of climate finance. Nature Climate Change 11, 180–182.

Rozenberg, J., Fay, M., 2019. Beyond the gap: How countries can afford the infrastructure they need while protecting the planet. World Bank Publications.

Russo, A., Mariani, M., Caragnano, A., 2021. Exploring the determinants of green bond issuance: Going beyond the long-lasting debate on performance consequences. Business Strategy and the Environment 30, 38–59.

Sachs, J.D., 2014. Climate change and intergenerational well-being. The Oxford handbook of the macroeconomics of global warming , 248–259.

Sack, B.P., Elsasser, R., 2004. Treasury inflation-indexed debt: a review of the us experience. Economic Policy Review 10.

Saeed, T., Bouri, E., Alsulami, H., 2021. Extreme return connectedness and its determinants between clean/green and dirty energy investments. Energy Economics 96, 105017.

Sangiorgi, I., Schopohl, L., 2021. Why do institutional investors buy green bonds: Evidence from a survey of european asset managers. International Review of Financial Analysis 75, 101738.

Sartzetakis, E.S., 2021. Green bonds as an instrument to finance low carbon transition. Economic Change and Restructuring 54, 755–779.

Schnabel, I., 2022. A new age of energy inflation: climateflation, fossilflation and greenflation, in: Speech given at a panel on "Monetary Policy and Climate Change" at The ECB and its Watchers XXII Conference, March.

Schwartz, E.S., 1982. The pricing of commodity-linked bonds. The journal of Finance 37, 525–539.

Schwartz, E.S., Moon, M., 2000. Rational pricing of internet companies. Financial Analysts Journal 56, 62–75.

Shiller, R.J., 2003. The invention of inflation-indexed bonds in early america.

Siemens, 2022. Siemens energy successfully places mandatory convertible bondin t he amount of eur960 million. https://press.siemens-energy.com/global/en/pressrelease/siemens-energy-successfullyplaces-mandatory-convertible-bond-amount-eur-960-million. last accessed 15 October 2022.

Simeth, N., 2022. The value of external reviews in the secondary green bond market. Finance Research Letters 46, 102306.

Smith, D.J., 2010. Alternative designs for inflation-indexed bonds: P-linkers vs. c-linkers. Journal of Financial Education , 111–132.

S&P, 2020. Falck renewables prices €200mgreenbondoffering. last accessed 5 November 2022.

Statista, 2022. European union emission trading system (eu-ets) carbon pricing in 2022. https://www.statista.com/statistics/1322214/carbon-prices-european-union-emission-trading-scheme/. last accessed 2 October 2022.

Stefan, M., Wellenreuther, C., 2020. London vs. leipzig: Price discovery of carbon futures during phase iii of the ets. Economics Letters 188, 108990.

Stiglitz, J.E., 2019. Addressing climate change through price and non-price interventions. European Economic Review 119, 594–612.

Stiglitz, J.E., Stern, N., Duan, M., Edenhofer, O., Giraud, G., Heal, G.M., La Rovere, E.L., Morris, A., Moyer, E., Pangestu, M., et al., 2017. Report of the high-level commission on carbon prices .

Stoll, C., Mehling, M.A., 2021. Climate change and carbon pricing: Overcoming three dimensions of failure. Energy Research & Social Science 77, 102062.

Sun, W., Huang, C., 2020. A carbon price prediction model based on secondary decomposition algorithm and optimized back propagation neural network. Journal of Cleaner Production 243, 118671.

Timperley, J., 2021. The broken $ 100-billion promise of climate finance - and how to fix it. Nature .

Tol, R.S., 2009. The economic effects of climate change. Journal of economic perspectives 23, 29–51.

Tolliver, C., Keeley, A.R., Managi, S., 2019. Green bonds for the paris agreement and sustainable development goals. Environmental Research Letters 14, 064009.

Tresor, A.F., 2022. 25 MAY 2022: LAUNCH OF THE NEW GREEN INFLATIONLINKED OAT€I 0.10 % 25JULY 2038 FOR AN AMOUNT OF €4BN. [Online; accessed28-September-2022].

Tvinnereim, E., 2014. The bears are right: Why cap-and-trade yields greater emission reductions than expected, and what that means for climate policy. Climatic Change 127, 447–461.

UN, 2022. Targets for the first commitment period: Mechanisms under the kyoto protocol - joint implementation. https://unfccc.int/process/the-kyoto-protocol/mechanisms/joint-implementation. last accessed 1 October 2022.

Venmans, F., Ellis, J., Nachtigall, D., 2020. Carbon pricing and competitiveness: are they at odds? Climate Policy 20, 1070–1091.

Voltalia, 2021. Voltalia's €200 million green convertible bond: a successful inaugural offering. https://gsh.cib.natixis.com/our-center-of-expertise/articles/voltalia-s-200-million-green-convertible-bond-a-successful-inaugural-offering. last accessed 5 November 2022.

van der Wiel, K., Batelaan, T.J., Wanders, N., 2022. Large increases of multi-year droughts in north-western europe in a warmer climate. Climate Dynamics , 1–20.

Worldbank, 2008a. Daiwa securities group offers the first cer-linked uridashi bond created in collaboration with the world bank. https://www.worldbank.org/en/news/press-release/2008/06/09/daiwa-securities-group-offers-the-first-cer-linked-uridashi-bond-created-in-collaboration-last accessed 15 October 2022.

Worldbank, 2008b. World bank launches its second cerlinked bond. https://www.worldbank.org/en/news/press-release/2008/09/12/world-bank-launches-its-second-cer-linked-bond. last accessed 15 October 2022.

Worldbank, 2022. Carbon pricing dashboard. https://carbonpricingdashboard.worldbank.org/. last accessed 2 October 2022.

Xiao, T., 2013. A simple and precise method for pricing convertible bond with credit risk. Journal of Derivatives & Hedge Funds 19, 259–277.

Zamarioli, L.H., Pauw, P., König, M., Chenet, H., 2021. The climate consistency goal and the transformation of global finance. Nature Climate Change 11, 578–583.

Zerbib, O.D., 2019. The effect of pro-environmental preferences on bond prices: Evidence from green bonds. Journal of Banking & Finance 98, 39–60.

Zhang, S., Yang, Z., Wang, S., 2020. Design of green bonds by double-barrier options. Discrete & Continuous Dynamical Systems-S 13, 1867.

Zhu, B., Chevallier, J., et al., 2017. Pricing and forecasting carbon markets. Springer.