Climate-Linked Bonds*

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Abstract

Climate-linked bonds, issued by governments and supranational organizations, are pivotal in advancing a net-zero economy. These bonds adjust their payoffs based on climate variables such as average temperature and greenhouse gas emissions, providing investors a hedge against long-term climate risks. They also signal government commitment to climate action and incentivize stronger policies. The price differential between climate-linked and nominal bonds reflects market expectations of climate risks. This paper introduces a model of climate hedging and estimates that approximately three percent of government debt in major economies could be converted into climate-linked bonds.

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1 Introduction

The world urgently requires decisive action to mitigate the impacts of climate change (IPCC, 2023; Ripple et al., 2024). Addressing climate change necessitates immediate and comprehensive efforts from all stakeholders, including companies in the real economy, financial institutions, consumers and, first and foremost, governments. The latter play a pivotal role in expediting the transition to a sustainable economy as they have the democratic and legal power to take strategic measures, such as appropriately pricing greenhouse gas emissions, curtailing subsidies to environmentally harmful activities, fostering the growth of sustainable finance, and backing innovation. Pricing and internalizing climate-related externalities emerges as the most economically impactful approach for reducing emissions, as it provides all stakeholders with a clear financial incentive to reduce their carbon footprints.[1] Furthermore, it is crucial for governments to create an environment that encourages technological innovation, to establish clear sustainability standards, and to utilize financial markets to mobilize resources, all of which are essential for driving the transition to a low-carbon economy.

We argue that governments and supranational organisations possess an additional, yet until now largely overlooked, policy instrument in the form of *climate-linked bonds*, which can actively contribute to the transition. The innovative financial instruments that we propose operate on the principle of adjusting their face value or coupon at regular intervals based on actual climate-related variables directly reflecting or driving environmental changes, such as the average land temperature, the annual concentration of greenhouse gases in a country's atmosphere, or water levels. The issuance of climate-linked bonds sends a credible signal that governments are committed to addressing the increasing intensity of climate damages associated with high emissions at an early stage and provides them with an additional fiscal incentive to confront climate challenge early

[1] See Pedersen (2023) who compares carbon taxes and green finance initiatives. While a carbon tax raises the cost of greenhouse gas emissions, green finance aims to fund activities that promote sustainability, leading to a differentiation in the cost of capital between sustainable and less sustainable firms. The author concludes that although these two policies can be seen as substitutes, a carbon tax aligned with the social cost of carbon is significantly more effective in reducing emissions.

on.[2] Moreover, by linking the payoff of climate-linked bonds to a variable correlated with climate damages, these instruments address the increasing demand for investments that hedge against long-term climate risks. Additionally, the distinct price differential between climate-linked bonds and nominal bonds serves as a valuable indicator of climate risks, offering crucial insights into investors' expectations.

The adjustment mechanics behind these bonds inherently mirrors the mechanism of *inflation-linked bonds*, whose nominal value or coupon adjusts with actual inflation. Many countries already issue inflation-linked bonds, offering an asset class which is risk-free in real terms, while allowing governments to make use of investors' willingness to accept lower yields in lieu of hedging inflation risk (Campbell et al., 2009; Bekaert and Wang, 2010). Similarly, climate-linked bonds can serve as a safe asset that shields investors from financial losses resulting from unmitigated climate risks.

In this paper, we explain what climate-linked bonds are and what benefits they offer for governments, investors, central banks, and for the financial system as a whole. We distinguish three main advantages of creating a market for climate risks through the issuance of these bonds. First, through market pricing, climate-linked bonds reduce the **information gap** on future climate risks and reveal the size of the climate risk premium. Incorporating these bonds into the financial system embeds climate risk into government balance sheets, clarifying and formalizing the government's role in tackling climate-related issues, especially during major external shocks.

Second, these bonds have the potential to reduce the **incentive gap** by aligning a government's financial interests with climate action. With a significant issuance of climate-linked debt, governments that successfully mitigate climate change would reduce their future fiscal burden by paying lower coupons on the debt. The incentive will be stronger the greater the issuing country's ability, through early transition policies, to influence the climate variable driving the bond's payoff. From this perspective, climate science can identify which long-term climate metrics most closely correlate with the

[2] In the theory of asymmetric information, the only credible signals are the costly ones, as they reveal the underlying nature and intentions of agents (Talmor, 1981). From that point of view, issuing specific instruments provides a costly and thus credible signal of the commitment to take action.

severity of climate damages. Economic analysis, in turn, can guide the choice of metrics, institutional frameworks, and financial designs that discourage free-riding and promote incentive alignment at the national level.

While this paper abstracts from institutional aspects and does not explicitly model incentive mechanisms, we acknowledge the critical role of global coordination in the effective issuance of climate-linked bonds. This challenge is similar to the coordination required for imposing global carbon taxes (Pedersen, 2023) and faces the same free-rider problem, where countries benefit from others' emission reductions without having sufficient incentive to act themselves. The issuance of climate-linked bonds can be viewed as a preliminary step toward forming a *climate club*, in the style of Nordhaus (2015).[3] Intertemporal free-riding—where current generations benefit from high carbon emissions while future generations bear the costs—poses a significant challenge. Financial markets, however, can play a pivotal role in addressing this issue. A credible transition policy can enhance market participants' expectations of long-term climate outcomes, reducing expected damages and lowering climate risk premia by mitigating climate uncertainty. This improvement in expectations will also be reflected in a lower present value of outstanding climate-linked debt, reducing the current government's debt-servicing costs and strengthening its credit position.

Third, climate-linked bonds can help in reducing the **insurance gap**. The instruments provide investors (e.g. insurers) with an opportunity to hedge against climate risks, thereby making the back-stop government support explicit that implicitly often already exists in the event of large natural disasters. Consequently, private parties, in particular insurers and re-insurers will be more inclined to take on some climate risk on their balance sheet, knowing that implicit government protection against tail risks is now made explicit. Hereby, we remark that it is widely expected that climate change will result in an increase of the frequency and intensity of extreme weather events (EEA, 2023), leading to significantly rising economic costs over the coming decades. Simultaneously,

[3] Nordhaus (2015) was the first to introduce the concept of a 'climate club,' in which countries committed to addressing climate change band together. By imposing tariffs on nonparticipants, climate clubs can incentivize broader participation and promote effective international climate policies.

the percentage of these costs that are insured is relatively low, a phenomenon referred to as the 'insurance gap' (ECB (2023)). The percentage of costs that are insured in the EU hovers around 35%, but in some countries, it bottoms out at only 5%. According to Swiss Re (2023), the global average is even higher, with only 45% of the $275 billion of catastrophe damages in 2022 being insured. In this context, we argue that climate-linked bonds can provide much needed help in the management of climate risks and in the looming transition towards a net-zero economy. Climate-linked bonds contribute to completing financial markets by creating a financial instrument to trade climate risks, factors that so far are difficult to hedge or price explicitly.

We argue that central banks can play a strategic role in supporting the climate-linked bond market also. By adding these instruments to their balance sheets, central banks can integrate climate considerations into their monetary policy frameworks and risk management strategies. This proactive stance can not only manage the central banks' own climate risk exposures but also set a precedent that encourages the broader adoption of sustainable finance practices. Central banks' involvement can thus act as a significant driver for establishing a robust and liquid market for climate-linked bonds.

Climate-linked bonds are closely related to existing financial instruments and concepts. Marketable financial instruments whose payoffs adjust based on the realization of an underlying climate variable are not new. Weather derivatives, whose payouts are a function of temperature, humidity, rain, or snowfall, have been traded since the late 1990s (Alaton et al., 2002; Yang et al., 2009), and are actively traded by energy and utility companies to hedge against temperature fluctuations that negatively affect their cash flows (Pérez-González and Yun, 2013). From this perspective, the infrastructure and knowledge needed to price climate-linked bonds already exist. Second, linking government bonds to macro variables is also not new. Next to inflation-linked bonds, Shiller (1998) proposes GDP-linked bonds, which tie debt servicing to a country's economic performance by linking payments to its GDP. In practice, GDP-linked bonds adjust interest payments or principal based on the issuing country's GDP growth rate, ensuring that payments increase when the economy is strong and decrease during economic downturns.

These bonds therefore offer issuers relief during downturns and provide investors with the potential for higher returns. The bonds reduce default risks and help stabilize economies during periods of financial stress (Benford et al., 2018).

Our contribution to the literature on climate economics and asset pricing can be summarized along four dimensions. First, we build on studies that explore hedging physical climate risk (Andersson et al., 2016; De Jong and Nguyen, 2016; Engle et al., 2020). These studies typically use the sensitivity of existing equity or fixed income securities to climate news to structure portfolios that serve as a long-term climate hedges. However, such strategies can be expensive due to high transaction costs from continuous rebalancing, and the hedge is often imperfect. Instead, we propose issuing a new financial instrument with a built-in adjustment mechanism that allows for a direct hedging of risks. Second, we extend previous examinations of climate-linked derivatives such as Bloch et al. (2010); Little et al. (2014, 2015); Chikhani and Renne (2022) and weather derivatives (Alaton et al., 2002; Benth and Benth, 2007). TThese studies, however, primarily emphasize the mathematical intricacies of valuing these instruments. In contrast, our focus is on the economic implications of climate-linked bonds, using a simple and intuitive model to underscore their risk-sharing benefits and their potential as a price discovery mechanism. This, in turn, could encourage the issuance of related derivatives, which may help close the climate insurance gap to the extent that it is driven by ambiguity about future climate damages (Tesselaar et al., 2022; Moore, 2024). Third, we contribute to the discussion on ESG-related instruments by situating the proposed investment vehicle within the broader context of alternative green investments (Baker et al., 2022; Kölbel and Lambillon, 2022) and catastrophe bonds (Morana and Sbrana, 2019), highlighting the unique features of climate-linked bonds. Fourth, we estimate the potential market side of climate-linked bonds based on an assessment of the government's role in absorbing the costs of climate change-related economic damages. We find that around three percent of outstanding government debt in large economies could be converted into climate-linked bonds.

The paper is structured as follows: Section 2 presents a stylized model of climate risk-sharing through climate-linked bonds and their pricing. Section 3 discusses the additional benefits of issuing such bonds. In Section 4, we estimate the potential market size of climate-linked bonds, address issues related to their structuring, examine the challenges of transparency and governance essential for establishing trust, and highlight the operational risks involved. Finally, Section 5 concludes.

2 Pricing of climate-linked financial instruments

In this section, we will delve into the pricing of climate-linked swaps and climate-linked bonds. First, we discuss a simple climate derivative instrument, the climate-linked swap, to illustrate how climate risk trading reveals the climate risk premium. Then, we will present a stylized model of climate risk pricing to illustrate the key mechanism and factors influencing the valuation of climate-linked bonds in equilibrium and the investment behavior of agents exposed to climate risk. Finally, we show how to derive market-consistent estimates of climate variables. In addition, for the interested reader Appendix A provides details on how climate-linked bonds relate to other fixed income instruments associated with climate objectives, and also how they differ.

2.1 Climate-linked swaps

We begin by offering insights into the market pricing dynamics that value future cash flows tied to the realization of a climate variable. We demonstrate that climate-linked swaps can reveal both the market-consistent expectations for the climate variable and the climate risk premium demanded by investors. Climate-linked swaps are particularly useful for this purpose, as they capture the core principles of risk transfer inherent in these financial instruments.

A climate-linked swap represents a financial agreement wherein the exposure to climate risk is transferred from one market party to another through a structured exchange of cash flows. Typically, this involves one party making fixed cash flow payments over the principal throughout the duration of the swap, while the counterparty makes variable interest rate payments tied to the realization of a specific climate variable. This dynamic mechanism enables market players to mitigate their exposure to climate-related uncertainties by offloading the associated risks to willing counterparties. At pre-specified coupon reset dates, the fixed and variable payments are reconciled and netted cash flows are exchanged between the two counterparties, reflecting the realized impact of the climate variable.

At the outset, the fixed swap rate is chosen so that the present value of the fixed payments equals the risk-adjusted present value of the expected variable rate payments. The fixed rate is also known as the price of the contract and reflects both the market-consistent expectation of the climate variable and a climate risk premium. This premium denotes the additional compensation demanded by market participants for bearing the risk related to the climate variable. This premium can theoretically be either negative or positive, depending on the assessed risk associated with the climate variable.

2.2 The climate risk premium

Thus, by pricing climate-linked instruments, the market reveals information about the expected climate risk premium, which can subsequently be used to price other financial instruments exposed to climate risk. To illustrate this point, we utilize the Stochastic Discount Factor (SDF). Any risky future payoff discounted by the SDF produces its fair market value. Intuitively, it can be seen as a discounting function across different states of the world. Agents are typically risk averse, so states of the world that result in lower cash flows would be discounted more heavily than ones that are profitable. As a result, the discounted future value of a risky asset will typically be lower than its expected value.[4]

For the sake of convenience, let us assume a climate-linked swap with a one-off payment exchange, with a nominal principal equal to one dollar, and maturing one period from now.[5] At the end of the term $\tau + 1$, one market party of the swap pays a fixed inter-

[4]It needs to be noted that under this simple statement lies extensive academic thought when applied to climate risk. There is significant debate on what constitutes risk aversion with respect to climate change (Litterman, 2011), another debate on the appropriate discount rate (Weitzman, 1998) and what discounting means in the face of climate damages and catastrophe risk (Barro, 2015; Martin and Pindyck, 2015), and a separate debate on how our inability to define the probabilities, and as a result expected values, of potential climate outcomes affects the pricing of climate risk (Olijslagers and van Wijnbergen, 2024). For the sake of brevity and clarity, we abstract from these complexities here.

[5]See Gamba-Mendez and Werner (2017) for an equivalent derivation of the inflation risk premium priced into inflation-linked swaps.

est rate ξ_τ on the principal, agreed in advance at period τ, in exchange for receiving an interest rate $S_{\tau+1}$ linked to the realization of the climate variable from the other market party. The fixed interest rate ξ_τ is the so-called climate-linked swap rate. Typically, the two market parties do not exchange cash flows at the beginning of the swap contract, so at the contract initiation date the price, or the current expected discounted value of the two separate cash flows of the swap's legs must be equal:

$$\mathbb{E}\left[M_{\tau+1}\xi_\tau\right] = \mathbb{E}\left[M_{\tau+1}\ S_{\tau+1}\right], \tag{1}$$

where $M_{\tau+1}$ is the stochastic discount factor and $\mathbb{E}$ the expectation value under the physical risk measure, conditional on the information available at time τ (Cochrane, 2005). We rewrite this equation by using the fact that at the start of the swap contract the climate-linked swap rate ξ_τ is fixed and observed in the market. Furthermore, for two stochastic variables X and Y the expected value of their product is given by $\mathbb{E}[XY] = \mathbb{E}[X]\mathbb{E}[Y] + \mathbb{Cov}(X, Y)$ We therefore can write:

$$\mathbb{E}\left[M_{\tau+1}\right]\xi_\tau = \mathbb{E}\left[M_{\tau+1}\right]\mathbb{E}\left[S_{\tau+1}\right] + \mathbb{Cov}\left(M_{\tau+1}, S_{\tau+1}\right).$$

Furthermore, we know that the expected value of the SDF will be the risk-free return (Cochrane, 2005), or $\mathbb{E}\left[M_{\tau+1}\right] = (1+r)^{-1}$. We can now derive the following expression for the climate-linked swap rate:

$$\xi_\tau = \mathbb{E}\left[S_{\tau+1}\right] + \underbrace{(1+r)\mathbb{Cov}\left[M_{\tau+1}, S_{\tau+1}\right]}_{\text{climate risk premium}}. \tag{2}$$

Equation 2 shows that the climate-linked swap rate ξ_τ as established by market supply and demand consists of two elements: the expected value $\mathbb{E}\left[S_{\tau+1}\right]$ or the market-consistent expectation of the climate variable and a climate risk premium $(1+r)\mathbb{Cov}\left[M_{\tau+1}, S_{\tau+1}\right]$. The risk premium is thus the compensation that investors demand for uncertainty around the expectation, and it depends on the correlation between the SDF and the asset cash flows. Intuitively, this implies that investors would be willing to pay a higher price today for assets with hedging properties in the future, i.e. having higher payoffs in bad states of the world when the SDF is also high. Equation (2) then suggests that the sign of the climate risk premium depends on the risk hedging properties of the asset, i.e. on the covariance term between the SDF and the future values of the asset. In the upcoming section we are going to discuss in more detail what these risks entail.

2.3 Climate-linked bond pricing in equilibrium

The discussion so far provides an initial intuition for pricing climate-linked swaps, based on a market-consistent expectation of the climate variable and the associated climate risk premium. Its implications extend to other climate-linked instruments. One can, in fact, think of a climate-linked bond investment as buying a nominal bond together with a climate-linked swap in which the investor pays a fixed rate and receives a floating rate based on the realization of the climate variable.[6] To further explore the key mechanism behind the pricing of climate risk bonds in equilibrium, we now build a stylized one-period model of an economy populated with agents who need to decide on their asset allocation under climate risk. We use a CARA-normal setup with simple climate dynamics to keep the problem analytically tractable.[7]

In this stylized setting, assume that there are two types of agents in this economy: a share δ of the population, which is exposed to potential climate damages, and a share $1-\delta$ that is not. For instance, this can represent municipalities or individuals facing economic losses due to sea-level rise or extreme heat, compared to those whose location protect them from such damages. We denote $i \in \{e, u\}$ as an index for the exposed and unexposed agents, respectively. Assume that all agents in the economy have a CARA utility over wealth y of the form:

$$u(y) = -\frac{1}{\alpha}e^{-\alpha y}, \tag{3}$$

where α is a coefficient of risk-aversion.

We will focus on temperature in the following discussion to provide a concrete context. However, the hedging arguments can also be generalized to other climate metrics, as

[6] This relates to the arbitrage strategy which replicates the payoff of an inflation-linked bond through an inflation-linked swap. See Fleckenstein et al. (2014).

[7] For studies relating the intricacies of climate dynamics with those of the dynamics of a production economy, especially within an asset pricing setting, we refer to Barnett et al. (2020) and Chikhani and Renne (2022).

discussed later on in Section 4.2. So, assume that the temperature difference relative to a reference temperature $\overline{T}$ is normally distributed, such that:

$$\Delta T \equiv T_{\tau+1} - \overline{T} \sim N(\mu, \sigma^2). \tag{4}$$

Herein, μ is the expected incremental temperature change over the investment horizon relative to the reference temperature and σ represents the volatility or uncertainty in the incremental temperature changes.[8] In this model, temperature fluctuations are treated as exogenous. This can be conceptualized as representing a small country whose economic activity does not significantly influence global climate change.

For simplicity, we furthermore assume that climate-related damages are a linear function of temperature changes:

$$D_{\tau+1} = d_0 + d_1 \Delta T + \epsilon_{\tau+1}. \tag{5}$$

In this function, $D_{\tau+1}$ represents the dollar amount of climate damages at time $\tau + 1$, d_0 denotes the baseline amount of damages irrespective of temperature change and d_1 is a sensitivity parameter that represents the amount of additional damages per unit of temperature change, with $d_1 > 0$ and $\epsilon_{\tau+1} \sim N(0, \sigma_{d,\epsilon})$ captures the idiosyncratic risk of damages not related to temperature increases.[9] The damages materialize at the horizon date and are directly subtracted from the final wealth of the exposed agents.

All agents in the economy make an investment plan at time τ for one period ahead. At time τ, they possess an endowment y_τ, which they can invest in risk-free bonds and in climate-linked bonds. Both types of bonds are zero-coupon bonds. The risk-free asset is priced at 1 and provides a gross payoff of R_f at the horizon date, where $R_f = (1 + r)$, with r being the one-period ahead risk-free rate. The climate-linked bond, priced at B_τ,

[8] In practice, $\overline{T}$ may be set to the expected future temperature, making μ zero. However, we maintain a more general setup to accommodate deviations in bond structures. Regardless, the choice of $\overline{T}$ will be reflected in the equilibrium bond price. Also, we abstract in our model from potential general equilibrium effects and the positive impact that the issuance of climate-linked bonds will have on the temperature dynamics. One can think of Equation 4 already reflecting this.

[9] We use a linear damage function to keep the model tractable and to illustrate the mechanism. In reality, the impact of extreme events is non-linear, increasing disproportionately with temperature change (Burke et al., 2015) and potentially subject to tipping points (Lenton et al., 2020). With non-linear damages, the case for climate-linked bonds quantitatively will be even stronger.

has a payoff at the horizon date that is linked to the realization of temperature changes. Specifically, the bond's payoff at $\tau + 1$ is given by:

$$B_{\tau+1} = b_0 + b_1 \Delta T. \tag{6}$$

Where b_0 is the face value or baseline dollar payment established at bond issuance, i.e., the payment of the bond if the actual temperature does not change relative to the reference temperature, $b_1 > 0$ is the coefficient that determines the sensitivity of the bond's payments to deviations in temperature, and $\Delta T = T_{\tau+1} - \overline{T}$ represents the change in temperature from the reference temperature.[10]

Let θ^i_τ denote the number of climate-linked bonds that agents of type i buy at time τ. The rest of their wealth is invest in risk-free bonds. The wealth of each type of agent at the horizon date can then be expressed as:

$$y^i_{\tau+1} = \theta^i_\tau B_{\tau+1} + (y_\tau - \theta^i_\tau B_\tau) R_f - D_{\tau+1} \mathbb{1}_i, \tag{7}$$

where $\mathbb{1}_i$, an indicator function equal to one if $i = e$ and zero otherwise. This function ensures that only the exposed agents are affected by the damages, which are subtracted from their end-of-period wealth.

It will be useful to rewrite this budget constraint, suppressing the time and investor type indices for θ and y_τ for brevity, as:

$$y_{\tau+1} = \underbrace{\theta(b_0 + b_1 \Delta T) - \theta B_\tau R_f - d_1 \Delta T \mathbb{1}_i + \epsilon \mathbb{1}_i}_{\equiv \Psi_{\tau+1}(\theta)} + y_\tau R_f - d_0 \mathbb{1}_i.$$

The CARA utility function ensures the following relationship:

$$\begin{aligned} \mathbb{E} u(y_{\tau+1}) &= \mathbb{E}\left(-\frac{1}{\alpha}\exp(-\alpha y_{\tau+1})\right) \\ &= -\frac{1}{\alpha}\exp\left(-\alpha(y_\tau R_f - d_0 \mathbb{1}_i)\right) \mathbb{E}(\exp(-\alpha \Psi_{\tau+1}(\theta))) \\ &\propto -\frac{1}{\alpha}\exp\left(-\alpha\left(\mathbb{E}\Psi_{\tau+1}(\theta) - \frac{\alpha}{2}\mathbb{V}\mathrm{ar}\Psi_{\tau+1}(\theta)\right)\right), \end{aligned} \tag{8}$$

where in the last step we make use of the mean and variance of a log-normal distribution.

[10] Climate-linked bonds can be structured to include either a fixed or floating nominal coupon, depending on the specific design and objectives of the bond. However, we omit this component to keep the model simpler and more tractable.

Note that without climate-linked bonds, exposed agents have no means to hedge against potential climate damages. The introduction of these bonds allows both types of agents to trade and manage climate risk effectively.[11]

So far we have laid down the pay-off structure of climate-linked bonds and the framework for investment decisions by all agents in our model. We now aim to determine the equilibrium price of climate-linked bonds based on two key conditions: (1) Each type of agent optimizes their asset holdings, and (2) The market clears in equilibrium, meaning that the total number of bonds bought by one party equals the total number sold by another party.

Agents optimize: Formally, we can write the optimization condition of the agents as:

$$\max_{\theta} \mathbb{E}u(y_{\tau+1}), \tag{9}$$

subject to the budget constraint in (7). In the CARA-normal case, using the relation in (8), this translates into maximizing the certainty equivalent of the form:

$$\max_{\theta} \left\{ \mathbb{E}(\Psi_{\tau+1}) - \frac{\alpha}{2} \mathbb{Var}(\Psi_{\tau+1}) \right\}, \tag{10}$$

where we have

$$\begin{aligned} \mathbb{E}(\Psi_{\tau+1}) &= \theta(b_0 + b_1\mu) - \theta B_\tau R_f - d_1\mu \mathbb{1}_i \\ \mathbb{Var}(\Psi_{\tau+1}) &= \sigma^2 \left(\theta b_1 - d_1 \mathbb{1}_i\right)^2 + \sigma^2_{d,\epsilon} \mathbb{1}_i. \end{aligned}$$

The first-order condition then ensures that, in optimality, bond holdings for each type of agent are:

$$\begin{aligned} \theta^i_\tau &= \frac{b_0 + b_1\mu - B_\tau R_f}{\alpha\sigma^2 b_1^2} + \frac{d_1}{b_1}\mathbb{1}_i \\ &= \underbrace{\frac{1}{\alpha\sqrt{\mathbb{Var}(B_{\tau+1})}} SR(B_{\tau+1})}_{\textbf{Investment Demand } \theta^i_{ID}} + \mathbb{1}_i \cdot \underbrace{\frac{\mathbb{Cov}(D_{\tau+1}, T_{\tau+1})}{\mathbb{Cov}(B_{\tau+1}, T_{\tau+1})}}_{\textbf{Hedging Demand } \theta^u_{HD}}, \end{aligned} \tag{11}$$

[11] We model the introduction and pricing of climate-linked bonds in a market setting where exposed and non-exposed agents freely trade. In practice, the government will play a role in issuing the bonds and will act as an intermediary between the agents exposed and the agents unexposed to climate damages.

where $SR(B_{\tau+1}) = \frac{\mathbb{E}(B_{\tau+1})-B_\tau R_f}{\sqrt{\mathbb{Var}(B_{\tau+1})}}$ is the Sharpe ratio of the climate-linked bond, with $\mathbb{Var}(B_{\tau+1})$ the variance of its payoff; and the ratio of co-variances measuring the relative sensitivity of damages and respectively bond payoffs to temperature changes.

Thus, we show that the agents' demand for climate-linked bonds can be separated into two terms: θ^i_{ID}, the investment demand, driven positively by the Sharpe ratio that these risky instruments offer, and negatively by the risk-aversion of the agents; and second, the hedging component θ^u_{HD}, relevant only for the agents exposed to climate change impacts, which is positively related to the bond sensitivity to damages.

The investment demand is negatively related to temperature variation, as this can be seen as the main risk driver for climate-linked bonds. Risk-averse investors reduce their demand for temperature-sensitive investments in case the risk is higher, leading to this inverse relationship. Note that the idiosyncratic risk of damages, represented by $\sigma_{d,\epsilon}$, does not affect the asset allocation decision. Since this specific risk of climate damages is unrelated to temperature change, it cannot be hedged using climate-linked bonds, whose returns are systematic and driven by temperature changes. Therefore, this idiosyncratic risk does not influence the investment demand for these bonds.

In our model, by construction, climate damages are perfectly correlated with the bond payoff, as both are affine transformations of the temperature variation. This implies that the impact of temperature changes can be perfectly hedged, and as a result, the hedging demand is independent of the temperature variance. It depends only on the relative sensitivity terms, d_1/b_1, as illustrated in (11).

Market clearing: The next step is to determine the market price of the climate-linked bond. To do this, we need to ensure that, at the bond issuance date, the amount of bonds issued is exactly matched by the amount purchased.[12] The market-clearing price of the bond will ensure that supply equals demand, such that the net amount outstanding is zero at the start of the period. We will show that, in equilibrium, the number of bonds purchased by the exposed agents equals the number of bonds supplied by the unexposed

[12]See Van Binsbergen et al. (2014) for a similar market clearing approach that allows pension funds with different age distributions to trade with each other.

agents, weighted by their relative sizes in the economy. For now, assume that the market clears, such that:

$$\delta\theta_\tau^e + (1-\delta)\theta_\tau^u = 0. \tag{12}$$

Substituting in the optimal bond holdings from (11) we get the equilibrium price of the climate linked bond:

$$\begin{aligned} B_\tau &= \frac{1}{R_f}\left(b_0 + b_1\mu + \delta\alpha\sigma^2 b_1 d_1\right) \\ &= \frac{1}{R_f}\mathbb{E}(B_{\tau+1}) + \frac{1}{R_f}\delta\alpha\mathbb{C}\mathbb{o}\mathbb{v}(B_{\tau+1}, D_{\tau+1}). \end{aligned} \tag{13}$$

The bond price thus consists of two components: the present discounted value of the expected payoff and the present discounted value of a risk component related to the covariance between the bond's payoff and climate damages.

Substituting the equilibrium bond price (13) back in the optimal holdings equation (12), we get:

$$\theta_\tau^e = \frac{(1-\delta)d_1}{b_1} > 0, \tag{14}$$

$$\theta_\tau^u = -\delta\frac{d_1}{b_1} < 0. \tag{15}$$

This implies that exposed agents will have a net positive demand for the bonds, while agents who are not exposed to damage are willing to issue climate-linked bonds because in expectation they earn a positive risk premium equal to $E(B_{\tau+1})/R_f - B_\tau$. Before we move on to the next subsection, it is important to note that, due to this positive risk premium, exposed agents also have an incentive to issue climate-linked bonds. However, their net demand for these bonds will remain positive because of their hedging needs. We will now continue to further explore the hedging dynamics.

Hedging demand and hedging supply: To gain intuition into the equilibrium pricing, we will break down total investments in to hedging demand and investment demand terms, as defined in Equation (11). We can then write the market-clearing condition in

(12) as:

$$\delta(\theta^e_{ID} + \theta^e_{HD}) + (1-\delta)\theta^u_{ID} = 0$$
$$\iff \delta\theta^e_{HD} = -\theta^u_{ID}, \tag{16}$$

where θ^u_{HD} stands for the hedging demand term that is applicable only to the exposed agents and we have used the fact that the investment demand term defined in (11) is the same for the exposed and the unexposed agents, i.e., $\theta^e_{ID} = \theta^u_{ID}$. Now, define the total amount of climate-linked bonds outstanding as f. This amount represents the equilibrium result of the supply of bonds f^s and the demand for climate-linked bonds f^d. Referring back to relation (16), we see that the aggregate demand for bonds is given by the hedging demand aggregated over all exposed agents:

$$f^d \equiv \delta\theta^e_{HD} = \delta\frac{d_1}{b_1} \tag{17}$$

The demand for climate-linked bonds is driven by the relative sensitivity of damages to temperature changes and the proportion of exposed agents within the population.

The aggregate supply on the other hand will be given by the investment demand aggregated over all - exposed and unexposed - agents, such that:

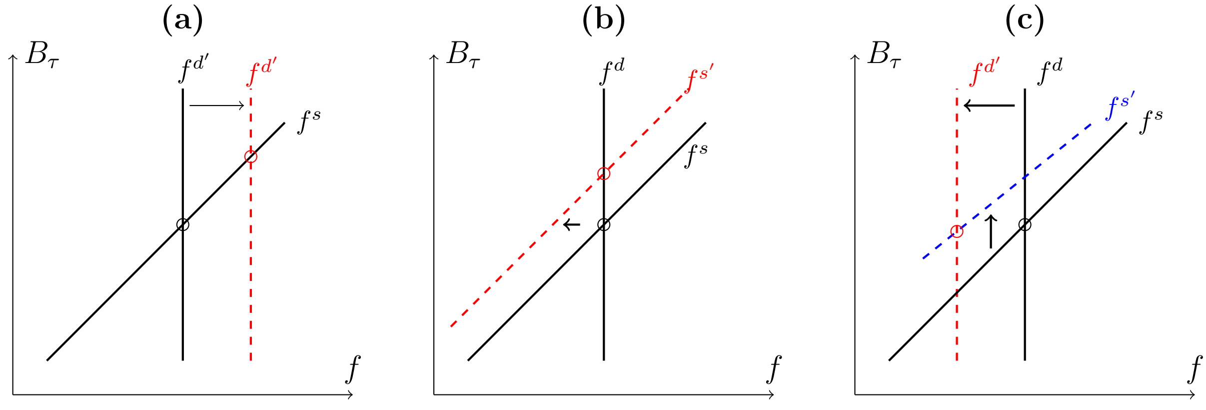
$$f^s \equiv -\theta^{e,u}_{ID} = \frac{R_f B_\tau - (b_0 + b_1\mu)}{\alpha\sigma^2 b_1^2}. \tag{18}$$

As a result, unlike the demand term discussed above, the supply of climate-linked bonds depends on the expected payoff and the variability of that payoff.

The equilibrium price of the bond and the equilibrium amount outstanding then will be at the point where the demand meets supply, as shown in Figure 1. Note that the demand for bonds is price-inelastic, while the willingness to issue bonds increases with a higher bond price. The hedging demand term in (11) remains unchanged because both damages and bond payoffs change by the same proportion with variations in temperature. We explore a calibration of the model in Appendix B to confirm numerically the findings below.

Using these relationships, we can gain intuition about how changes in various factors affect the price and total amount of climate-linked bonds outstanding. In Panel (a) of

Figure 1: Demand and supply for climate-linked bonds



Note. This figure shows the aggregate hedging demand and supply curves. Panel (a) shows the impact of a higher share of exposed agents δ in the economy, Panel (b) plots the impact of a higher expected temperature μ, Panel (c) reveals the impact of a higher sensitivity of the bond's payments to deviations in temperature b_1.

Figure 1, we see that increasing the share of exposed agents in the economy increases the aggregate hedging demand, shifting the demand curve f^d to the right, while the hedging supply curve remains unchanged. As a result, in order to balance demand and supply, the price of climate-linked bonds increases. In equilibrium, we observe a higher amount of bonds issued and a higher bond price. The same holds true if the sensitivity of climate damages to temperature (d_1) increases.

Panel (b) shows the impact on the equilibrium of a higher expected temperature, μ. This results in a lower hedging supply, holding everything else constant, thereby shifting the supply curve f^s to the left. The hedging demand curve f^d remains unchanged, as it is purely driven by the co-variation of the bond with climate damages. In equilibrium, to induce unexposed agents to increase the supply of hedging again, the price of the climate-linked bond must rise. It is also interesting to observe that while the temperature variance affects the equilibrium price level of the bond in Equation (13), it does not appear in the equilibrium investment levels of (14) and (15). To understand why this is not the case, note that the hedging demand is fixed and independent of the temperature variance. Consequently, as shown again in Panel (B), any increase in σ^2 only shifts up the supply curve f^s. This implies that bond prices have to increase in order to induce agents to supply the same level of hedging as before.

Panel (c) reveals the impact of an increased bond sensitivity to climate changes, b_1. When this parameter rises, bonds become more effective at hedging climate damages, which initially shifts the demand curve f^d to the left, as agents need less bonds in order to achieve the same level of hedging damages. At the same time, increased bond sensitivity also shifts up and flattens the supply curve, as higher sensitivity to temperature changes increases the expected payoff at maturity, while also increasing the variance of the bonds. The overall effect will be a lower equilibrium level of outstanding bonds. Whether this results in lower or higher bond prices depends on the slope of the f^s curve and the magnitude of the shift. We now continue with deriving the SDF.

Completing the market and deriving the stochastic discount factor: The introduction of a market for climate-linked bonds is key in pricing climate risk. As we have illustrated, this is crucial for enhancing market-based risk-sharing between agents. It should also be noted that the existence of a liquid climate-linked bond market will improve the availability and pricing of other climate-contingent claims, thereby fostering climate risk insurance. With the establishment of a market for climate risk, we can determine the stochastic discount factor (SDF) that will be used to price other climate-contingent products as well.

Formally, the prices of the risk-free bond and the climate bond together uniquely define the Stochastic Discount Factor (SDF) $M_{\tau+1}$ can be used to price any other climate-contingent payoff:

$$\begin{aligned} E(R_f M_{\tau+1}) &= 1, \\ E(B_{\tau+1} M_{\tau+1}) &= B_\tau. \end{aligned} \tag{19}$$

We can use this system of equations to solve for the exact form of SDF as a function of the model parameters. To do so, we first guess that the SDF is linear in the temperature change, the systematic risk factor in this model:

$$M_{\tau+1} = m_0 + m_1 \Delta T. \tag{20}$$

We can then substitute this in (19) to verify that the guess is correct and to find the two parameters:

$$\begin{aligned} m_0 &= \frac{1}{R_f}\left(1 - \mu\delta\alpha d_1\right), \\ m_1 &= \frac{\delta\alpha d_1}{R_f}. \end{aligned} \tag{21}$$

The positive slope coefficient m_1 then implies, as conjectured earlier, that in equilibrium, assets that pay off when the temperature is high will receive a high weight, meaning they will be discounted less heavily in their valuation (see also Litterman (2011)). In fact, when individuals' risk aversion, the share of agents exposed to damages, or the sensitivity of damages to temperature changes are higher, these assets will be even more valuable.

The climate risk premium: The SDF also gives the size of the climate risk premium in equilibrium. Following the approach in Equation 2, we can write the climate-linked bond price as the sum of the expected payoff and a climate risk premium:

$$\begin{aligned} B_\tau &= \mathbb{E}(M_{\tau+1})\mathbb{E}(B_{\tau+1}) + \mathbb{Cov}(M_{\tau+1}, B_{\tau+1}) \\ \implies B_\tau &= \underbrace{\frac{1}{R_f}\mathbb{E}(B_{\tau+1})}_{\text{Expected Payoff}} + \underbrace{\delta\alpha d_1^2\sigma^2}_{\text{Climate Risk Premium}}. \end{aligned} \tag{22}$$

As we predicted earlier, the climate risk premium will be positive as $\delta\alpha d_1^2\sigma^2 > 0$. We now move on to discuss the pricing of climate-linked derivatives.

Pricing climate-linked derivatives: As mentioned earlier, we can use the SDF from the previous section to price other climate-linked securities. To illustrate this, consider pricing a call option on temperature with a strike temperature T^s, which may differ from the reference temperature $\overline{T}$. The call option's payoff at time $\tau + 1$ can be expressed as:

$$\begin{aligned} C_{\tau+1} &= \max(T_{\tau+1} - T^s, 0) \\ &= \max(T_{\tau+1} - \overline{T} - T^s + \overline{T}, 0) \\ &\equiv \max(\Delta T_{\tau+1} - (T^s - \overline{T}), 0). \end{aligned}$$

We can then derive the current price of the call option using the SDF as follows:

$$\begin{aligned} C_\tau &= \mathbb{E}\left(M_{\tau+1}C_{\tau+1}\right) \\ &= \mathbb{P}(\Delta T_{\tau+1} > 0)\mathbb{E}\left(M_{\tau+1}\left(\Delta T_{\tau+1} - (T^s - \overline{T})\right)\right), \end{aligned}$$

where $\mathbb{P}$ denotes the physical probability that the option will have a non-zero payoff at maturity. Given the assumptions on the distribution of temperature changes relative to the reference value in (4), the probability that the option expires in-the-money can be expressed as:

$$\mathbb{P}(\Delta T_{\tau+1} - (T^s - \overline{T}) > 0) = 1 - \mathbb{P}(\Delta T_{\tau+1} \leq T^s - \overline{T}) = \Phi\left(\frac{\mu - (T^s - \overline{T})}{\sigma}\right),$$

where $\Phi(.)$ stands for the standard normal distribution. Note that for a higher expected temperature change, μ, or for a lower strike, T^s, the probability that the call option expires in-the-money increases. The option price can then be written as:

$$C_\tau = \frac{1}{R_f}\Phi\left(\frac{\mu - (T^s - \overline{T})}{\sigma}\right)\left(\mu + d_1\delta\alpha\sigma^2 - (T^s - \overline{T})\right), \tag{23}$$

where we have substituted the derived SDF from (20) and (21), and utilized the fact that $\mathbb{E}\left((\Delta T)^2\right) = \mu^2 + \sigma^2$. In Appendix B we how the option value and the exercise probability are sensitive to changes in temperature volatility and the option strike.

2.4 Market-consistent climate expectations

So far, we have shown the potential for a climate-linked bonds market in which the demand for climate hedging meets the supply by agents willing to exploit the instruments' favorable funding rates. Based on our stylized model, we derived an analytical expression for the bond's price, balancing supply and demand factors. In practice, prices will be observed in the market. Given a liquid market for these instruments, the prices will reflect the views of investors and issuers and their willingness to trade on the future development of climate variables. These prices can then be used in structural asset pricing models to infer market-based views on future risk developments, similar to how volatility is implied by the Black-Scholes-Merton model of option pricing, see, e.g. Bodie and Merton (1995). We illustrate this point with our stylized model.

Assume that prices B_τ^{obs} for a bond with given parameters of the coupon structure, b_0 and b_1, are observed in the market. Assuming that the model in Section 2.3 correctly describes the economy and that δ, d_1, and σ^2 can be reliably parameterized by climate specialists, we can use the bond prices to derive market-based climate expectations. Since (13) is one equation with two unknowns, we can estimate the market-consistent expected incremental temperature change for a given level of variance:

$$\hat{\mu} = \frac{B_\tau^{obs} R_f - b_0 - \delta\alpha\sigma^2 b_1 d_1}{b_1}. \tag{24}$$

In this case, it is clear that that a higher observed bond price implies a higher expected incremental temperature change.[13] Alternatively, calibrating to a given expected temperature μ, we can estimate the expected variance of temperature deviations:

$$\hat{\sigma}^2 = \frac{B_\tau^{obs} R_f - b_0 - b_1\mu}{\delta\alpha b_1 d_1}. \tag{25}$$

Again, it is clear that a higher observed bond price implies a higher temperature variance. The rationale is that with higher variance, issuers of the bond need to be offered higher prices in order to lure them to accept sponsoring the climate hedge.

3 The benefits of climate-linked bonds

As demonstrated analytically in the previous section, climate-linked bonds offer risk-sharing benefits to both issuers and investors. They also incentivize governments to take climate action, encourage central banks to green their monetary operations, and enhance the financial system by facilitating price discovery and improving information flow. In this section, we discuss these implications in detail.

3.1 Benefits for governments

First, governments issuing climate-linked bonds may benefit from the favorable pricing and lower yields often observed for labeled bonds in high demand. Historically, ESG-

[13] The required volatility parameter can be derived forward looking using expert climate knowledge or climate models, or alternatively, estimated by extrapolating historical or cross-sectional temperature patterns. In the case of a liquid market with bond options, the volatility parameter could also be linked to the implied volatility from these options.

related labeled bonds have benefited from a price premium and accompanying yield benefit; an effect that was defined as the so-called ‘greenium’ for green bonds (Eskildsen et al., 2024). In our pricing model from Section 2, we showed why climate-linked bonds can ex ante be subject to a similar price premium.

In addition, the issuance and performance of climate-linked bonds create a fiscal incentive for governments to proactively address and combat climate change. By linking the government’s financial obligations to climate-related variables, the bonds encourage sustained and robust policy efforts across successive administrations. By aligning sustainability objectives with financial considerations, the instrument internalizes, at least partially, the existing climate externalities. In the absence of adequate climate mitigation measures, through climate-linked bonds governments directly face the consequence of elevated greenhouse gas concentrations, as the coupons or face value on their issued debt adjust as a form of penalty. This mechanism aligns *ex-ante* the economic interests of governments with the imperative to implement effective climate policies that would reduce long-term physical risks due to climate change.[14] Further, climate-linked bonds promote transparency and accountability in climate policy for instance through disclosing the market’s expectation on emission reductions.[15]

Third, extreme climate change-related damages often surpass the financial and infrastructural capacities of private institutions and households, in practice implicitly positioning governments as the insurers of last resort. This implicit role becomes explicit through the issuance of climate-linked bonds. These bonds make the government’s financial responsibility for climate-related damages transparent and predictable. By linking financial obligations to climate variables, climate-linked bonds formalize the government’s commitment to proactive climate risk management.

It is important to note that, unlike catastrophe bonds, the occurrence of a single climate disaster event does not affect the payoff of climate-linked bonds, nor does it

[14] See also Ando et al. (2022) for the benefits for governments to issue climate debt instruments.

[15] Van Wijnbergen and Willems (2015) demonstrate that even climate skeptics have an incentive to reduce emissions, which further bolsters the argument for integrating climate risk into financial instruments like bonds.

impact the government's costs of servicing any climate-related debt. The climate variables driving bond payoffs, such as average land temperature, typically change gradually rather than abruptly year to year. This stability is crucial for governments, which may face cash constraints precisely when disaster relief funding is most needed. Meanwhile, over the long term, payments servicing climate-linked bonds flow directly to investors, who are likely exposed to future climate risks. This structure explicitly defines the government's role as an insurer in the economy, formalizing a commitment that is often implicit during major climate-related events.

The bonds also exert a disciplining effect. Given the long maturities of these instruments, and the tendency of efficient markets to quickly discount future payoffs, if a government contributes to the worsening of climate variables by following an unsustainable climate policy, the expected increase in future cash outflows to service climate debt will likely raise yields on all government bonds. To avoid this, a government would be incentivized *ex-ante* to return to sustainable climate policies.

3.2 Benefits for private investors

Climate-linked bonds offer private investors a unique opportunity to effectively hedge against climate risks while aligning their investment strategies with long-term environmental objectives. First, climate-linked bonds present an attractive investment opportunity for institutional investors such as pension funds, insurance companies, and sovereign wealth funds. It is well understood that investors currently lack effective climate hedges. Existing strategies for mitigating climate risk often involve sophisticated and costly dynamic rebalancing in response to climate news (Andersson et al., 2016; De Jong and Nguyen, 2016; Engle et al., 2020). Climate-linked bonds offer a more efficient solution for this purpose. The coupon adjustment mechanism, when structured to respond to temperature rises, sea level rises, or water levels in rivers, provides investors with an extra return if the global transition to a low-carbon economy does not occur in a timely and efficient manner, and higher intensity of heat waves, floods, or similar natural catastrophes materializes. In these cases, high physical risk can be expected to impede economic growth and depress the return on traditional asset classes such as bonds and equity. In addition, Dietz et al. (2016) estimate that under a business-as-usual scenario, the climate Value at Risk (the potential tail loss on the present market value of global financial assets) stands at 1.8%, or \$2.5 trillion with 95% confidence, and with the 99-th percentile even reaches 16.9%, or \$24.2 trillion, indicative of the extreme risk that climate risk poses. Climate-linked bonds thus serve as assets that can hedge this risk, at least to some extent. This type of climate hedging could be particularly valuable for insurers providing (re)insurance against natural catastrophes.

Second, climate-linked bonds facilitate the sharing of physical climate risks between governments and private (re)insurance parties, alleviating the burden on insurers. The instrument makes government support explicit for investors and insurers. This backstop support often already implicitly exists in the event of large natural disasters. By establishing this support mechanism proactively, governments are incentivized to address climate change from the outset.

Third, by investing in climate-linked bonds, institutional investors demonstrate their commitment to responsible investing and contribute to the transition to a low-carbon economy by financially incentivizing governments to actively pursue this transition. Unlike green bonds, climate-linked bonds do not incur additional costs for monitoring and verifying the environmental credentials of the product. Instead, they are tied to broad climate targets rather than specific environmental spending goals.

Fourth, climate-linked bonds offer diversification benefits to portfolios. Similar to catastrophe bonds, their returns tend to be less correlated with the business cycle, providing diversification opportunities compared to traditional asset classes. This makes them a valuable complement to investors' standard strategic asset allocation frameworks.

3.3 Benefits for central banks

In light of the growing urgency to address climate change, central banks are increasingly recognizing the importance of incorporating climate considerations into their policy frameworks. Additionally, with the advent of Quantitative Easing, central banks in developed countries have become significant asset owners, and the composition of their balance sheets now has considerable implications for the broader market (Campiglio et al., 2018). Climate-linked bonds offer an opportunity for central banks to align their monetary operations with climate objectives, while enhancing financial resilience and contributing to the transition to a sustainable economy for three main reasons.

First, climate-linked bonds provide central banks with an instrument to diversify their asset portfolios and mitigate climate risks, similar to regular investors (Broeders and Schlooz, 2021). By incorporating climate risk considerations into their asset purchase programs, central banks can better protect their balance sheet against the potential adverse impacts of climate change on financial markets and the broader economy. These bonds offer a means for central banks to manage their exposure to climate risks, such as physical damage from extreme weather events or transition risks associated with the shift to a low-carbon economy.

Second, by actively participating in the market for climate-linked bonds, central banks will signal a commitment to address climate change. This encourages other market participants to follow, thereby catalyzing broader adoption of sustainable finance practices. By targeting investments in bonds linked to climate-related indicators, central banks can support efforts to mitigate greenhouse gas emissions, promote renewable energy development, and enhance climate resilience. Aligning monetary policy with climate policy objectives can contribute to a more coordinated and potentially more effective response to the climate crisis, provided that the alignment is carefully managed and integrated with key objectives of price and financial stability.

Third, central bank involvement in the secondary market for climate-linked bonds, for example through asset purchase programs in times of crisis or a structural portfolio in normal times to provide liquidity to the financial system, can help foster the development of a robust and liquid market for these instruments. As key players in financial markets, central banks have the potential to influence market dynamics and incentivize the issuance and trading of climate-linked bonds.

3.4 Benefits for the financial system

For the financial system as a whole, climate-linked bonds provide crucial informational value. The market-driven pricing mechanism of climate bonds, influenced by supply and demand dynamics, facilitates *price discovery*. Comparative analysis of climate-linked bonds against nominal bonds enables the deduction of market-consistent expectations for the underlying climate variable, along with an additional risk premium. Since climate-linked bonds address the materialization of long-term physical risks, it is advisable to structure them across various long-term maturities, e.g. 30 to 50 years or even longer, allowing markets to establish a comprehensive term structure for climate risks and presenting an attractive alternative for long-term investors, such as pension funds, typically exposed to the financial risks arising from climate damages.

Climate-linked bonds can be instrumental in addressing the insurance protection gap, which refers to the portion of climate damages that remain uninsured. Globally, just 45% of catastrophe damages were insured in 2022. Further, only about 35% of climate-related costs in the EU are insured, with some countries as low as 5% (ECB, 2023). This significant percentage of uninsured damages places a heavy financial burden on governments in the aftermath of extreme weather events. By investing in government-issued climate-linked bonds, investors can decide how much climate risk they are willing to take on and what portion requires hedging. As a result, climate-linked bonds ensure that a larger share of climate risks is proactively addressed through financial markets, rather than relying on ad-hoc governmental interventions post-disaster.

Overall, we argue that climate-linked bonds, by employing both risk transfer mechanisms and enhancing transparency regarding government backstop support, have the potential to bolster the involvement of financial markets in addressing physical climate risks.

4 Practical considerations when issuing climate-linked bonds

In this section, we elaborate on several important elements regarding the implementation of climate-linked bonds in the financial system, including the potential market size, climate-linked bond specifications, challenges in constructing climate-linked securities, and, finally, operational and implementation risks.

4.1 The potential market size of climate-linked bonds

When implemented, climate-linked bonds could replace some of the outstanding conventional bonds that make up a country's nominal debt.[16] In this section, we estimate the potential market size of the climate-linked bond market in several advanced economies. To do so, we take a more practical approach to the equilibrium of supply and demand for hedging assumed earlier. We assume that the per-period expected damages related to climate change equal the per-period cash flows from the climate-linked bonds to the extent to which they are covered by the government.

First, assume that the expected temperature increases over a projection horizon of h are μ. The one-period expected losses as a percent of GDP are then given by $d_1\frac{\mu}{h}$. Second, assume that the total issued amount of the bonds in local currency, again as a percent of GDP, is f, and the bonds have a built-in coupon adjustment mechanism such that the expected coupon payment per period is $b_1\frac{\mu}{h}$. Additionally, each period, a fraction $1/m$ of the climate-linked bonds will redeem back and will also be used by investors to cover climate damages, where m is the average duration of the bonds outstanding. Using our earlier notation, we have:

$$\begin{aligned} d_1\frac{\mu}{h} &= b_1\frac{\mu}{h}f + \frac{1}{m}f \\ \implies f &= \frac{d_1\mu/h}{b_1\mu/h + \frac{1}{m}}. \end{aligned} \tag{26}$$

We estimate the market size using Equation (26) for a number of large economies in Table 1. For the average loss in GDP for a one-degree increase in temperature, we

[16] Recall that the proceeds from climate-linked bonds serve general financing needs.

use Bilal and Känzig (2024), who estimate a long-term negative impact of 12 percent ($d_1 = 0.12$). For the estimated increase in temperature per country, we use data from Berkeley Earth.[17] Table 1 shows the estimated increase in temperature by 2100, or about $h = 75$ years from now. We set the sensitivity of payments to deviations in temperature, b_1, equal to d_1 ($b_1 = d_1 = 0.12$). Finally, we assume that each country's agency will set the duration of the climate-linked bonds portfolio m equal to the duration of the current bond portfolio, sourced from Bloomberg. The average market size for climate-linked bonds across these economies is 1.9 percent of GDP, with some variation: for example, it is 1.4 percent of GDP for Germany and 2.3 percent of GDP for China. The fraction of the climate-linked bond portfolio relative to current marketable debt is, on average, 2.7 percent. For the US, this ratio is 1.9 percent, while for China, it would be 5.0 percent. The expected temperature increase is 1.7°C, with an uncertainty of $\sigma_{\Delta T} = 1.1$°C. We compare this baseline figure with a case in which the governments wants to cover an extreme-case scenario, defined as two standard deviations increase in temperature ($\Delta T + 2\sigma_{\Delta T}$). In that case the proportion of climate-linked bonds relative to current marketable debt would rise to 6.2 percent ($\approx 2.7 \times \frac{1.7+2\times 1.1}{1.7}$).

Table 1: Estimated market size of climate-linked bonds for large economies

Variable/country	Canada	China	France	Germany	Japan	Neth.	UK	US
ΔGDP/1°C (d_1)	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12
ΔT by 2100 (°C)	3.10	2.40	1.30	1.30	1.40	1.20	0.90	2.10
$\sigma_{\Delta T}$ (°C)	1.40	1.17	0.94	1.25	1.09	1.17	1.09	0.62
Number of years	75	75	75	75	75	75	75	75
Bond sensitivity (b_1)	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12
Duration (m, years)	6.06	6.04	8.18	6.90	8.45	8.68	13.96	5.83
Market size/GDP (f)	2.9%	2.3%	1.7%	1.4%	1.9%	1.6%	2.0%	1.9%
Debt/GDP	0.59	0.45	1.05	0.60	2.07	0.49	1.04	1.03
Market size/debt	4.9%	5.0%	1.6%	2.4%	0.9%	3.4%	1.9%	1.9%

Note. The market size is estimated using Equation 26 with data from Bilal and Känzig (2024), who estimate a 12% GDP loss per 1°C increase. Temperature increases ΔT by 2100 and uncertainty around this estimate increase $\sigma_{\Delta T}$ are based on Berkeley Earth data `https://berkeleyearth.org/policy-insights/`. We assume payment sensitivity ($b_1 = d_1 = 0.12$, and bond portfolio duration (m) matches the current portfolio duration, according to Bloomberg. Market size/GDP shows the climate-linked bond portfolio as a fraction of GDP (f). Debt/GDP is the ratio of current outstanding marketable debt to GDP. The final row is the market size of climate-linked bonds to marketable debt. Neth. is short for the Netherlands.

[17] See `https://berkeleyearth.org/policy-insights/`.

One of the crucial assumptions in this analysis is the number of years over which the expected increase in temperature occurs. Figure 2 illustrates how the average market size for the eight countries varies depending on the number of years over which the expected temperature increase is projected to occur. Naturally, if the number of years decreases, the annual losses related to climate change would be higher, leading to an increase in the issuance of climate-linked bonds relative to GDP.

It is important to note that our analysis does not account for the possibility that by issuing climate-linked bonds, governments may have an incentive to implement policy measures to combat climate change, potentially reducing the estimated losses (measured by d_1). We leave this feedback mechanism for future research.

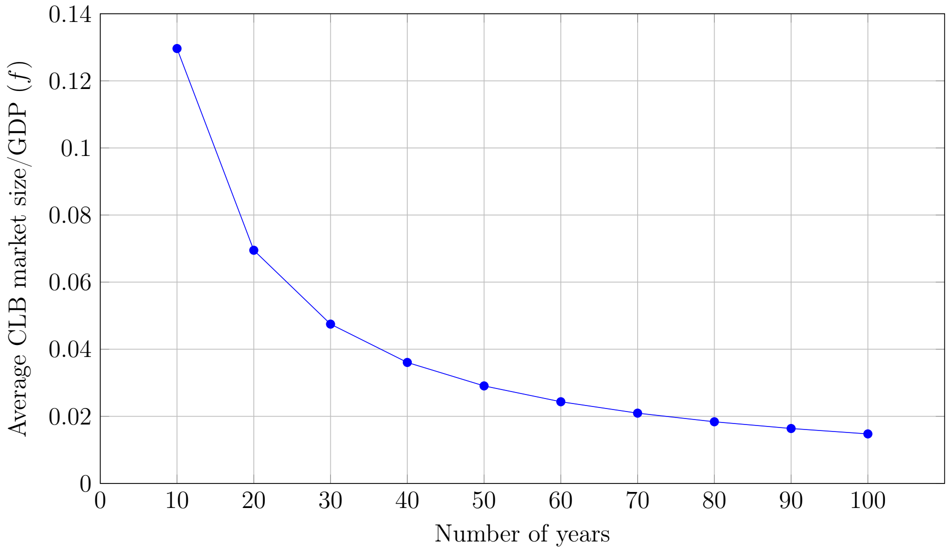


Figure 2: Market size relative to GDP over time horizons of climate change

Note. The figure shows the equally weighted average market size of climate-linked bonds relative to GDP as a function of the number of years over which the expected increase in temperature occurs across Canada, China, France, Germany, Japan, the Netherlands, UK, and the US with data from Bilal and Känzig (2024), Berkeley Earth data `https://berkeleyearth.org/policy-insights/` and Bloomberg. The results are based on Equation 26.

4.2 Climate-linked bond specifications

The payoff of a climate-linked bond is adjusted based on a physical variable that reflects climate change dynamics. In this section, we will discuss in more detail the climate variables that can define the payoff of these bonds.

4.2.1 Temperature

When constructing climate-linked bonds, a potentially useful climate variable is the temperature anomaly, which refers to the deviation of a specific temperature measurement from the long-term average for a given location and time period. It is typically expressed as the difference between the observed temperature and the average temperature over a reference period, often calculated as a baseline average temperature for the same location over some years.[18] Positive temperature anomalies indicate temperatures warmer than the long-term average, while negative anomalies indicate temperatures cooler than average. At bond issuance a reference temperature $\overline{T}$ at time τ is taken as the benchmark. Deviations from the reference temperature over time lead to changes in the pay-off. One potential amendment to the pay-off specification in equation (6) is to constrain the bond pay-off to be non-negative all the time:

$$B'_{\tau+1} = b_0 + \max(b_1 \Delta T, 0). \tag{27}$$

The maximum operator thus ensures that the payment cannot become negative and represents an implicit put option embedded in the bond's payoff.[19] The formula indicates that if the observed temperature exceeds the reference temperature, the payment for that period will increase. However, if the observed temperature falls below the reference, the payment will not decrease below the agreed-upon base amount. The magnitude of the change in payments depends on the coefficient b_1. Parameters b_0 and b_1 can be based on market conditions, and such that the price volatility of the bond and its sensitivity to temperature changes are within an acceptable range.

Temperature movements can be specified in different ways, each influencing the issuing government's incentives. Global Land Surface Temperature (LST) offers a broad perspective on climate change trends and could serve as a standardized reference for globally issued climate-linked bonds, enhancing liquidity. In contrast, local or regional LST may better reflect local damages, such as heatwaves, droughts, and biodiversity loss, and

[18] Appendix C presents the annual temperature anomalies for large economies since 2000.

[19] In practice, inflation-linked bonds adjust the principal using an index ratio, calculated as the ratio of the CPI at the reference (issue) date to the current CPI. However, to prevent negative coupons, there is a floor on the principal, Barnes et al. (2010).

could be politically more acceptable. Tying national public debt to local LST also mitigates free-riding, as policies affecting land use, urbanization, and deforestation directly impact local LST.

4.2.2 Greenhouse gas emission and concentration levels

A similar framework can be applied to climate variables more directly influenced by human activity, such as greenhouse gas (GHG) emissions. For example, at the time of bond issuance, a forward-looking reference level for GHG emissions aligned with the targets of the Paris Agreement can be established as a benchmark. Positive deviations from this benchmark then determine the bond's payoff. This linkage directly incentivizes governments to implement policies aimed at reducing GHG emissions and upholding climate initiatives, ultimately leading to lower debt funding costs.[20] From this perspective, climate-linked bonds are closely related to the class of sustainability-linked bonds discussed in Annex A. Furthermore, given that GHG emissions in the short run correlate strongly with economic activity, such climate-linked bonds align with the standard fiscal objective of maintaining sustainable debt levels with low default risk. They do so without constraining a country's deficit during economic downturns, thereby acting as automatic stabilizers akin to GDP-linked bonds (Shiller, 1998).

4.2.3 Water levels

In certain cases, investors may face 'two-way' climate risk, where both high and low values of a climate variable increase risk. For example, consider a climate-linked bond with a payoff tied to groundwater or lake and reservoir levels. Climate change affects precipitation patterns, leading to fluctuations in the water stored in lakes and reservoirs. On one hand, this can result in reduced water levels, droughts, and heatwaves, which are increasingly associated with climate damages. On the other hand, it may also lead to more intense rainfall and an increased risk of flooding. Thus, assuming that the deviation ΔW represents the difference between observed water levels and a reference

[20] See Appendix D for CO_2-trajectories for major economies, highlighting deviations from the 1991-2020 average CO_2 emissions from fossil fuels and industry, excluding land-use changes.

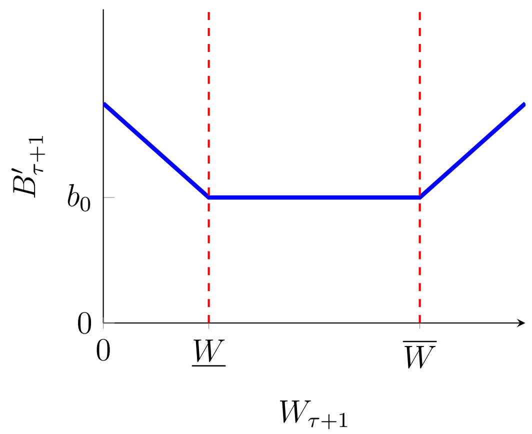
level both excessively high water levels (indicating flood risk) and excessively low water levels (indicating water scarcity) can pose risks. To address this, the bond's sensitivity to water level changes, $\Delta W_{\tau+1}$, can be structured to account for both high and low extremes while avoiding negative payoffs. This design can be particularly appealing for investors looking to hedge against both droughts and floods.

One approach is to structure the payoff so that it provides returns when water levels are either below a threshold $\underline{W}$ (risk of drought) or above a threshold $\overline{W}$ (risk of flooding). For thresholds where $\underline{W} < \overline{W}$, the payoff function can be defined as:

$$B'_{\tau+1} = b_0 + b_1 \max(W_{\tau+1} - \overline{W}, 0) + b_2 \min(\underline{W} - W_{\tau+1}, 0), \tag{28}$$

where b_0 is a base amount, b_1 and b_2 are sensitivity coefficients for high and low water levels, respectively. Figure 3 illustrates this concept. In structured finance, this type of payoff structure is known as a 'strangle,' which involves embedding both a long call and a long put option on the underlying variable. This setup provides protection against extreme values in either direction. However, it's important to note that incorporating these options into the bond payoff increases the bond's cost for investors. This is because the protection provided by the options comes with an upfront cost, making the bond more expensive.

Figure 3: The payoff of a bond responsive to climate extremes in both directions



Note. This figure shows the potential structure of a climate-linked bond payoff structure to pay off in extremely high or low realization of the variable $W_{\tau+1}$. When tied to the realization of water levels, this could be attractive for example for investors looking to hedge at the same time the risk of flooding and the risk of droughts.

4.3 Challenges in constructing climate-linked securities

Ideally, governments and supranational organizations play a pivotal role in the issuance of climate-linked bonds, aiming to foster a robust and liquid global market. However, integrating three key objectives — providing financial incentives, acting as a hedging instrument, and serving as a reliable source of information — presents significant challenges. The success of climate-linked bonds depends on their level of standardization across markets and cost-effectiveness to achieve substantial scale.

Typically, investors attach an additional cost to complex financial products due to the need to understand their underlying intricacies (Sato, 2014; Thakor and Merton, 2023). To address this, it is crucial to align the design of climate-linked bonds with investors' hedging preferences, thereby reducing the risk associated with a mismatch between the chosen variable and the climate risks investors face. For a robust market, consistent and large-scale issuance of these bonds is essential, and this can be supported by governments and supranational organizations. Their involvement is critical in fostering a global market that achieves significant scale and uniformity, making these bonds more cost-effective and mitigating the additional costs associated with complex financial products.

Another significant challenge is ensuring sufficient liquidity and offering a broad range of maturities. A liquid market facilitates easier buying and selling of bonds, attracting more investors and enhancing price discovery. Adequate diversity in maturities is crucial for constructing a comprehensive term structure of climate risks. This diversity helps investors and issuers better understand and manage climate risks over their relevant time horizons. For instance, property and casualty (P&C) insurers typically have short-term liabilities related to claims payments for damages and repairs, while pension funds generally have long-term exposures and liabilities. For both types of insurers, climate-linked bonds can be a part of their hedging strategy, but this segmentation underscores the importance of offering bonds with various maturities to meet the needs of different investor types and to improve overall market efficiency.

Furthermore, for climate-linked bonds to effectively achieve environmental goals, governments need to exert some influence over the climate variables associated with these bonds. This influence is vital for ensuring that the bonds' performance aligns with targeted environmental outcomes. However, achieving this alignment is complicated by the inherently unpredictable and complex nature of climate-related factors. Effective implementation of these bonds often requires international or even global coordination to address climate risks comprehensively and uniformly. Such coordination helps ensure that climate-linked bonds are integrated into broader environmental strategies and that efforts to mitigate and adapt to climate change are consistent across borders.

One challenge in constructing an adjustment mechanism that effectively hedges against climate risk is the potential for tipping points in climate change, where damages may increase exponentially after reaching a certain threshold (Lenton et al., 2020). To address this, the coupon structure of climate-linked bonds can be designed to be non-linear with respect to temperature. The key challenge is to align *ex ante* the sensitivity of the coupon structure to temperature with the sensitivity of climate damages to temperature.

4.4 Basis risk for investors

Investors will experience *basis risk* when investing in climate-linked bonds. This basis risk arises when the climate-related variables used to adjust the bonds' payoffs do not perfectly correlate with the investors' actual climate risk exposures or damages. In the context of hedging against climate-related damages, it is key to acknowledge three sources of long-term uncertainty:

1. **Emission Levels:** The amount of greenhouse gas emissions in the coming decades is uncertain, largely depending on current and future policy decisions, technological advancements, and societal changes. It is important to note that a bond linked to a country's emissions would directly address this source of uncertainty.

2. **Climate Sensitivity:** There is scientific uncertainty about how much the global temperature will increase given a certain concentration of emissions. The climate

system can change due to feedback processes, such as cloud cover, ice-albedo feedback, and carbon cycle responses, which makes precise quantification of climate sensitivity difficult. Based on current scientific estimates, if carbon concentrations double from pre-industrial levels, global average temperatures are expected to increase by 2°C to 4.5°C (Sherwood et al., 2020). However, there is potential for higher sensitivity due to tipping points IPCC (2021).

3. **Economic Damages:** Another source of uncertainty is the extent of economic damages, in monetary terms, that will result from a given level of temperature increase. These damages can vary widely depending on geographic location, economic resilience, and adaptive capacity.

Climate-linked bonds, especially those tied to temperature or emissions, are designed to mitigate the first and, to some extent, the second sources of uncertainty related to climate damage. However, the third source of uncertainty—the actual monetary damages that an investor experiences following increases in the climate variable—remains a significant residual risk. To manage this type of basis risk, investors can diversify their portfolios of climate-linked bonds across different climate variables, thereby spreading the risk and reducing the likelihood that a single uncorrelated event will significantly impact their overall hedging strategy.

For a more exact hedge against specific climate risks, investors can also consider catastrophe bonds or private insurance contracts. These options are likely to become more widely available as private (re-)insurers can hedge their aggregate, diversified exposure across individual insurance contracts by investing in these bonds.

4.5 Political aspects of climate bond issuance

A potential concern with climate policies is the long transmission lag or significant delay between the implementation of policies designed to reduce climate emissions and the observable effects on climate-related variables, such as average land temperature or water levels.[21] This delay poses a challenge in providing immediate feedback on the effectiveness of climate policies.

Additionally, government debt can be strategically used to impose constraints on future politicians, particularly those from a different party than the incumbent (Alesina and Tabellini, 1990). This raises questions about the efficacy of climate-linked bonds as financial incentives for governments to combat climate change, especially given the long transmission lags associated with climate policies.

However, several arguments counter this concern. Firstly, issuing these bonds with various maturities means that the political party in power today could indirectly bind itself if climate policies are unsuccessful, as the financial repercussions would span multiple terms. Conversely, successful climate policies would alleviate future financial obligations related to these bonds, benefiting the issuing party. Secondly, climate-linked bonds provide immediate feedback and incentives at the time of issuance, as their parameters are determined based on market perceptions at that moment. Thirdly, it is important to note that climate-linked bonds are likely to constitute only a small fraction of total government debt. This limited proportion ensures that while climate-linked bonds offer valuable signals and incentives, they do not dominate the government's overall debt structure, thus mitigating concerns about long-term political and financial impacts.

It should also be noted that individual governments only partially control the underlying variables of climate-linked bonds. Even if a government implements effective policies and adaptation measures, the reference variable underlying a climate-linked bond can still fluctuate due to the policies of other governments. As a result, *free-riding* effects are a key concern in the policy debate surrounding climate change and the energy transition.

When the underlying variable is global temperature, for example, some countries have an incentive to rely on the policies of larger players; especially those with a limited ability to impact the variable. As noted earlier, the institutional setting of a climate club, in the style of Nordhaus (2015), can provide additional external motivation for governments to

[21] Transmission lags are longest for temperatures, but for intermediate variables such as greenhouse gas emissions, the transmission lag will be shorter.

adhere to their climate obligations.[22] The international policies imposed by a climate club are likely to be more stringent, given that the issuance of climate-linked bonds provides national climate policies with a direct financial dimension.

Also, geographical factors, that cannot be influenced by governments can influence climate variables. Additionally, there is the issue of climate justice: some governments have contributed more to climate change in the past than others. As a result, the effectiveness of the incentives in climate-linked bonds increases as more governments collaborate and issue this instrument or if the bonds are issued at a supranational level.

4.6 Implementation and operational risks

Climate-linked bonds offer many benefits, but they also carry operational and implementation risks. These risks can be mitigated through precise calibration of adjustment mechanisms, transparent data reporting, robust governance frameworks, and advanced data collection and analysis technologies.

The calibration of adjustment mechanisms must be transparent and precise to maintain investor confidence. Any lack of clarity or perceived manipulation in how climate variables are measured and adjusted could harm the credibility of these instruments. To ensure accurate calibration, adjustments in coupon or face value must accurately reflect the underlying climate processes. Inaccurate calibration can lead to mispricing of the bonds, eroding investor confidence and reducing their attractiveness.

Overall, transparency in how climate variables are measured and reported is essential. This requires the use of reliable data sources and clear, consistent and stable methodologies for data collection and analysis. Any ambiguity or perceived manipulation in the data can undermine the credibility of the bonds, making them less appealing to investors. Transparent reporting standards are necessary to provide investors with regular and accurate updates on performance. This includes detailed disclosures on how climate variables are measured, how adjustments are calculated, and any changes in the methodologies

[22]More recently, Bolton et al. (2024) also suggest coalitions of advanced economies to prevent free riding in the context of large-scale climate finance.

used. Regular reporting helps to build trust and confidence among investors, making climate-linked bonds a more attractive investment option.

To further ensure the integrity and reliability of climate-linked bonds, robust governance frameworks are essential. This includes clear guidelines for data collection, calibration of adjustment mechanisms, and reporting standards. Independent oversight bodies can play a crucial role in monitoring compliance with these guidelines and ensuring that the bonds are managed transparently and effectively. To mitigate operational risks, issuers of climate-linked bonds should invest in robust data collection and analysis infrastructure. This includes leveraging advanced technologies such as satellite imaging, remote sensing, and climate modelling to gather accurate and real-time data on climate variables. Issuers should also establish clear protocols for data validation and verification to ensure the integrity of the information used for bond adjustments.

5 Conclusion

The introduction of climate-linked bonds represents an important step towards enhancing the comprehensiveness of financial markets, while concurrently providing a more tangible framework for measuring and mitigating climate risks. By incorporating climate-linked bonds into the financial landscape, the exposure to climate risks becomes intricately woven into the fabric of the government's balance sheet and the issuance of climate-linked bonds serves to explicitly delineate and formalize the government's role in addressing climate-related challenges, especially when confronted with significant external shocks. For investors, climate-linked bonds provide an investment opportunity that can fall within their ESG mandate and can be interpreted as a new asset class.

In this paper, we highlight how a liquid market for climate bonds *ex-ante* offers favorable pricing for issuers, such as national governments or supranational organizations, while providing long-term climate risk hedging opportunities for investors, including insurance companies and pension funds that are exposed to chronic losses resulting from climate change. Both advantages reflect the supply and demand for the innovative instruments. The hedging capabilities of climate-linked bonds are shown by how closely the bond payouts track the damages linked to the climate variable, such as temperature changes, emissions, or river water levels.

Furthermore, we explain how the pricing of climate-linked bonds provides information on the expected level of the climate variable (e.g. the expected temperature rise) as well as the perceived variance around this expectation, which we interpret as climate risk premium. We argue that this price discovery mechanism in the climate-linked bond market assists in the adequate pricing of climate risk. As we illustrate, this is crucial for enhancing market-based risk-sharing between agents. Moreover, we contend that a liquid climate-linked bond market improves the availability and pricing of other climate-contingent claims, thereby fostering climate risk insurance.

The concepts we present can be extended to nature-linked bonds. This can be achieved by applying similar principles while focusing on variables related to environmental conservation and biodiversity. For instance, the face value or coupon payments of nature-linked bonds could be tied to metrics such as deforestation rates, wildlife populations, or water quality indicators. Like climate-linked bonds, nature-linked bonds incentivize governments to protect and restore natural ecosystems. Additionally, these bonds can serve as a tool for investors to hedge against environmental risks while promoting sustainable practices. By expanding the scope of climate-linked bonds to include nature-related variables, governments and investors can collectively contribute to preserving ecosystems and biodiversity, ultimately leading to a more sustainable and resilient future. In the case of nature-linked bonds, governments can likely influence the relevant metrics more directly because biodiversity effects are often more regional.

Overall, climate-linked bonds (or nature-linked bonds) provide an opportunity to hedge against key risks, making explicit the government support that often implicitly exists in the event of large natural disasters. As we have illustrated, these instruments further complete financial markets in the context of the looming transitions toward addressing climate change and achieving a net-zero economy. By integrating these bonds into investment strategies, stakeholders can better align their portfolios with climate action goals and contribute to more effective climate risk mitigation.

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A Taxonomy of green investment vehicles

Climate-linked bonds serve as a financial instrument for governments or supranational organizations to secure funding while addressing climate change concerns. The bonds are designed to meet general financing needs but have a unique feature: their face value or coupon adjusts periodically based on pre-specified indicators linked to climate risks. These indicators are continuous variables that reflect climate change. Examples of such variables include the annual concentration of atmospheric greenhouse gases, average land temperature, or sea and river water levels. The calibration of the adjustments must be conducted meticulously and transparently to instill confidence in the instrument's reliability and effectiveness. This requires balancing investors' hedging needs while keeping the bonds' credit risk contained. Climate-linked bonds are distinct from other types of environmental, social, and governance (ESG) bonds that exist financial markets in several specific ways.[23]

First, many ESG-labeled bonds, such as *green bonds*, require the collected proceeds to be earmarked specifically to eco-friendly projects (Baker et al., 2022; Monasterolo et al., 2024; Vladimirova and Fang-Klingler, 2024). These projects typically focus on renewable energy, energy efficiency, pollution prevention, sustainable agriculture, or clean transportation. Green bonds can be issued by governments, corporations, or financial institutions. Their coupon can be fixed or floating but is not tied to a specific variable of target. By purchasing green bonds, investors help to finance initiatives that address climate change or foster sustainability. Currently, these types of bonds, with earmarked proceeds, constitute the vast majority of the outstanding ESG-labeled bond space, see Table (2).

A second category exists, *sustainability-linked bonds* (SLBs), which does not earmark the proceeds to be used for financing ESG projects. Instead, the sustainability commitment of these bonds hinges on meeting self-selected and self-imposed ESG targets by the

[23] Alternatively, one can refer to Green, Social, and Sustainability-Linked Securities (GSSS), which are financial instruments issued to fund projects or activities with positive environmental, social, or sustainability impacts.

issuer (Kölbel and Lambillon, 2022; Chen et al., 2023).[24] The coupon embeds a step-up or step-down structure tied to the achievement of these specific sustainability targets, such as reducing carbon emissions or even broader social goals such as increasing the share of female board members. SLBs have so far mostly been issued by corporations, but more recently also some sovereign issuers have participated as well.[25] Generally, SLBs are tied to an action over which the issuer has direct power. As such they are distinct from climate-linked bonds, which can be related to a variable that is less directly controlled by the government, such as temperatures or water levels. Additionally, the step-up or step-down feature in SLBs is generally structured as a binary adjustment, triggered by the achievement of specific goals, rather than as a continuous variable. This distinguishes SLBs from climate-linked bonds.

Third, a distinct category is formed by *catastrophe bonds*. The proceeds from issuing 'cat bonds' are typically placed into a special-purpose vehicle (SPV), which holds the funds in trust, and then their payoff is tied to the occurrence of pre-specified natural disasters (Morana and Sbrana, 2019) such as hurricanes or earthquakes. If no trigger event occurs during the life of the bond, investors receive their full principal back at maturity along with the coupon payments they have earned. However, if a qualifying catastrophic event occurs, the SPV uses the funds to pay the issuer's claims, and the investors lose part or all of their principal. Re-insurers in particular, utilize catastrophe bonds to transfer risks to investors. The market size of catastrophe bonds and similar insurance-linked securities is estimated to be around $50 billion, although the market is rather opaque.[26] Recently, the governments of Mexico and Jamaica, with the help of

[24]These targets or objectives are typically (i) measured through predefined Key Performance Indicators (KPIs) and (ii) assessed against predefined Sustainability Performance Targets (SPTs), see `https://www.icmagroup.org/assets/documents/Sustainable-finance/2024-updates/Sustainability-Linked-Bond-Principles-June-2024.pdf`.

[25]Chile and Uruguay notably have issued SLBs with sustainability targets related to the reduction of sovereign carbon emissions, increasing renewable energy production, increasing the share of female board members of state-owned companies and finally on nature protection areas.See https://sslburuguay.mef.gub.uy/.

[26]Estimated market size, based on data by ILS cat bond & insurance-linked securities research firm Artemis, available at: `https://www.artemis.bm/dashboard/`.

the World Bank, have issued cat bonds, as well as Puerto Rico on its own, echoing the potential for risk sharing and risk transfer also for climate-linked bonds.[27]

Climate-linked bonds differ from catastrophe bonds in several ways. First, they feature a gradual pay-off structure, where the payout changes incrementally with variations in the underlying climate variable. In contrast, catastrophe bonds have a binary payout, which is either triggered or not by a specific event. Additionally, cat bonds provide financial protection to the issuer, which justifies the higher yields they typically offer to attract investors. Climate-linked bonds, on the other hand, offer protection to the investors and thus, as we will show in Section 2, justify lower yields, securing more favorable upfront financing costs for the issuer compared to a similar instrument that does not include the coupon adjustment mechanism. Second, while catastrophe bonds, are becoming more narrowly focused in the type of disasters they cover due to the increasing variety and intensity of climate-related damages, thus limiting their coverage, climate-linked bonds, can be tied to a broader range of climate variables, offering more comprehensive protection. Lastly, since governments are typically the primary issuers of climate-linked bonds, they have a direct incentive to implement policies that reduce climate risks, thereby lowering their future financing costs. This incentive is generally absent in the issuance of catastrophe bonds by (re)insurer companies.

B Model calibration: bond and option prices

Figure 4 explores numerically how the bond price and the bond holdings of the exposed agents depend on (1) the fraction δ of agents exposed, (2) the uncertainty σ around the expected temperature, (3) the sensitivity b_1 of the climate-linked bond's pay off to the climate variable, (4) the risk aversion α. Our estimates provide a rough estimate based on the stylized model that we have explored. For the baseline calibration, we consider a 30-year investment horizon and take the risk-free return to be $R_f = 1.8$, which is roughly the accumulated wealth invested at a 2% interest rate over that period. Assuming that

[27] See press releases at https://www.worldbank.org/ for April 17 and April 25 2024; and https://www.artemis.bm/news as of June 25, 2024.

Table 2: Comparison of climate-linked bonds and ESG bonds

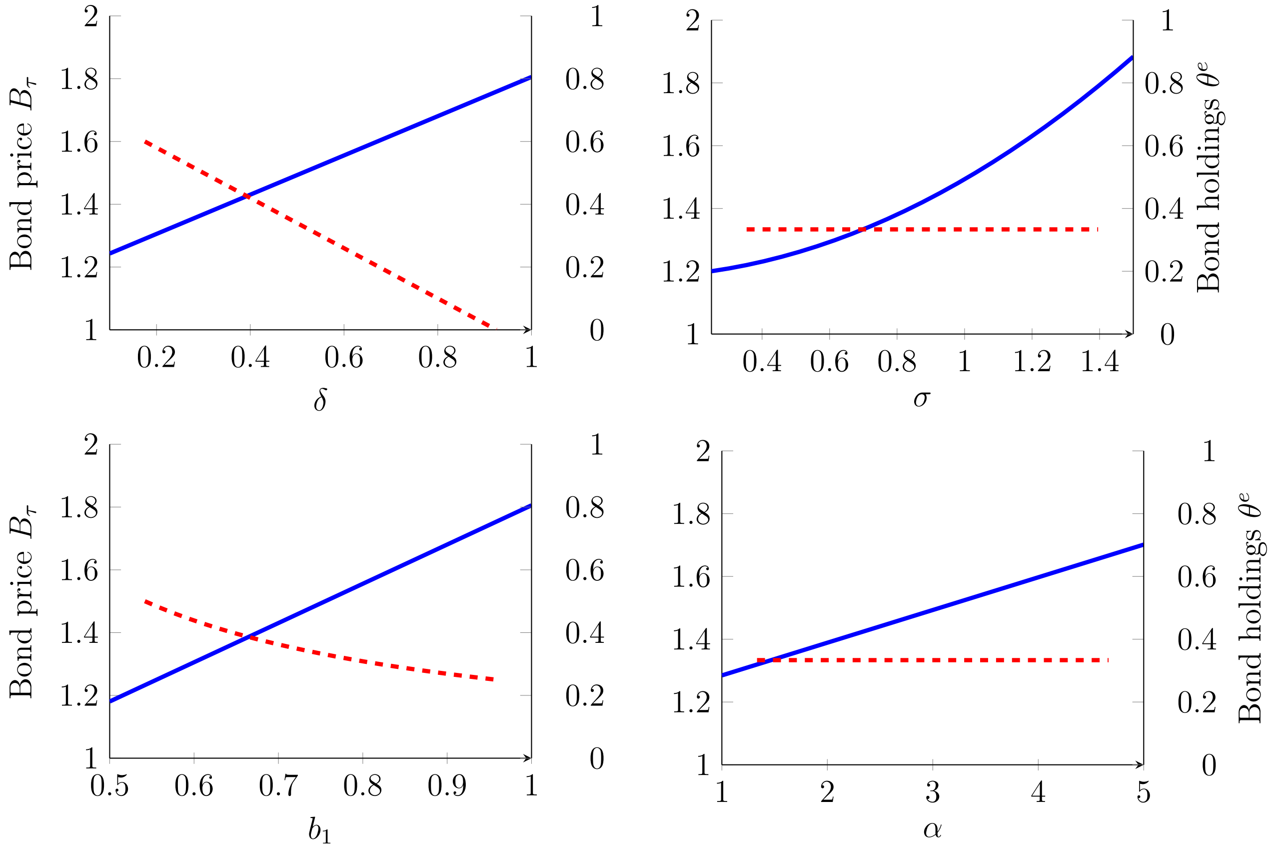
Type of bond	Proceeds from bond issuance	Payoff on the bond	Main issuers	Market size (bn USD)
Climate-linked bonds	Used for general financing needs	Periodically adjusted coupon or face value based on the realization of a climate variable	Governments	-
Green bonds	Used to finance eco-friendly projects	Fixed or floating coupon, not linked to a specific variable	Both public and private sector parties	$2,700bln
Sustainability-linked bonds	Used for general financing needs	Linked to the achievement of a specific self-imposed sustainability target	Mainly companies but few government issues exist (Chile, Uruguay)	$330bln
Catastrophe bonds & insurance-linked securities	Placed into a special-purpose vehicle which manages the collateral and the payoffs to the investor and sponsor	Coupon payments to the investor and/or principal drops if triggers based on specific catastrophic events are hit. The sponsor receives a pre-specified payment.	Insurance and reinsurance companies	$50bln

Note. This table provides a comparison between climate-linked bonds and other types of ESG-labeled bonds. We source the market size for outstanding green and sustainability-linked bonds from Bloomberg, based on the self-reported features of the bonds. For green bonds, we apply the *Green bond/loan indicator* from Bloomberg, which indicates whether the issuer states that "proceeds of the instrument include environmental projects or activities." For sustainability-linked bonds, we apply the *Sustainability linked indicator* from Bloomberg, which indicates whether the issuer states that "the instrument includes issuer-predefined, forward-looking, performance-based organizational sustainability targets." The catastrophe bond market size is sourced from Artemis and includes both outstanding catastrophe bonds and other similar so-called insurance-linked securities.

the reference temperature $\overline{T}$ equals the current temperature, we assume an expected temperature change of 1.5 degrees Celsius, with a standard deviation of 1 degree. In terms of damages, we assume that for every degree increase in temperature, the exposed individuals face a financial damage of 50 cents per euro currently invested.

We can observe from the figures the relationships that were already suggested analytically: a higher proportion of exposed agents increases the *aggregate* hedging demand, which in turn leads to a higher bond price, which in turn, in equilibrium lowers the *individual* holdings of exposed agents, θ^e, for the bond. Similarly, higher risk aversion, temperature variance, and bond payoff sensitivity to temperature increase the price of the bond. Note that the optimal holdings of climate-linked bonds in the second figure does not depend on climate change uncertainty (σ). This is easy to see because in equilibrium the optimal bond holdings for individuals only depends on the share of exposed agents (δ) in the economy and the sensitivities of the bonds (b_1) and damages (d_1) to climate change (Equation (14)).

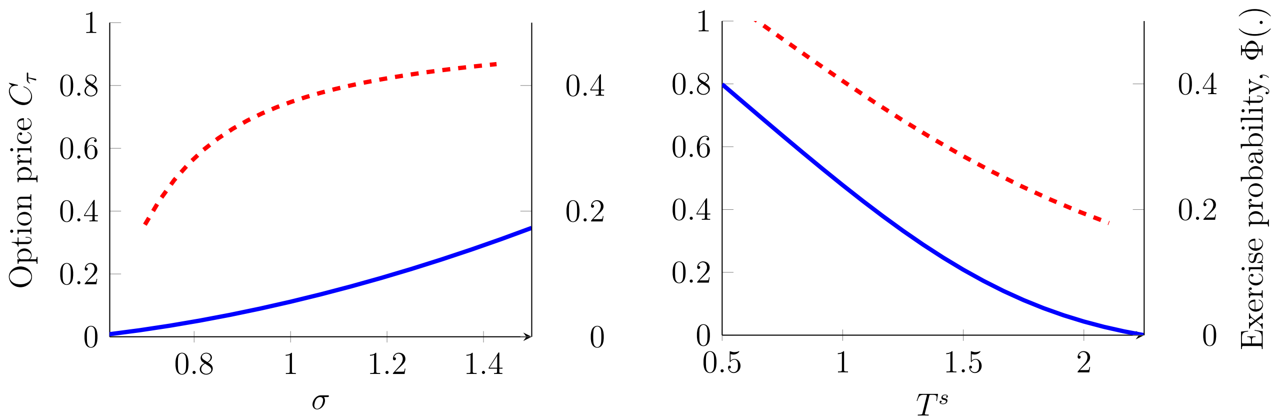
Figure 4: Equilibrium pricing: Bond price (solid blue, lhs) and demand (dashed red, rhs) of the exposed agents for climate-linked bonds



Note. This figure shows the relationship between bond price and demand under various parameters. The charts illustrate the effects of varying (1) the fraction of exposed agents (δ), (2) the impact of temperature standard deviation in degrees Celsius (σ), (3) the sensitivity of the climate bond (b_1) to temperature, and (4) the risk aversion of agents. For the baseline calibration we use a risk-free return of $R_f = 1.8$, risk aversion $\alpha = 3$, expected temperature change $\mu = 1.5$ degrees, standard deviation of $\sigma = 1$ degree, strike $T^s = 1.75$, damage sensitivity to climate change $d_1 = 0.5$, fraction of exposed $\delta = 0.5$, and bond sensitivity to climate change $b_1 = 0.75$, with $b_0 = 1$.

We can also price call options following the model in Section 2. Figure 5 illustrates the sensitivity of the option value and the exercise probability to changes in temperature volatility and the option strike. As expected, higher temperature variance increases the likelihood that an out-of-the-money option will be exercised, thereby increasing its value. Conversely, a higher strike reduces the chances that the option will be exercised at maturity, thus lowering its current price.[28]

Figure 5: Call option price (solid blue, lhs) and probability of exercise (dashed red, rhs)



Note. This figure shows the relationship between the call option price and the probability of exercise under varying parameters. The left-hand panel illustrates the effects of varying (1) the temperature standard deviation (σ) for a given option strike of $T^s = 1.75$ and (2) an expected temperature change of $\mu = 1.5$. The right-hand panel shows how the option price and exercise probability negatively depend on the strike price T^s. For the baseline calibration, we use a risk-free return of $R_f = 1.8$, risk aversion $\alpha = 3$, expected temperature change $\mu = 1.5$ degrees, standard deviation of $\sigma = 1$ degree, and damage sensitivity to climate change $d_1 = 0.5$, share of exposed agents $\delta = 0.5$.

C Temperature anomalies

Figure 6 shows annual temperature anomalies for large economies since 2000, indicating deviations from the 1991-2020 average surface temperature in degrees Celsius. These figures highlight the variations in average temperatures each year. This data provides an indication of how the coupons on climate-linked bonds, which are linked to these anomalies, could vary over time. The mean temperature anomaly for the US is 0.234 degrees Celsius with a standard deviation of 0.469 degrees Celsius on an annual basis. Germany experienced the largest temperature anomaly on average, at 0.308 degrees Celsius over last 24 years. Canada shows the highest standard deviation, which is 0.782 degrees Celsius.

There are a couple of implications for setting the pay-off structure. First, if the temperature unit changes, the anomaly calculation will be different, and thus the pay-off

[28]It is important to note that, in our setup, the distribution of future temperatures is fixed relative to $\overline{T}$, so the current temperature does not feature in the option pricing equation.

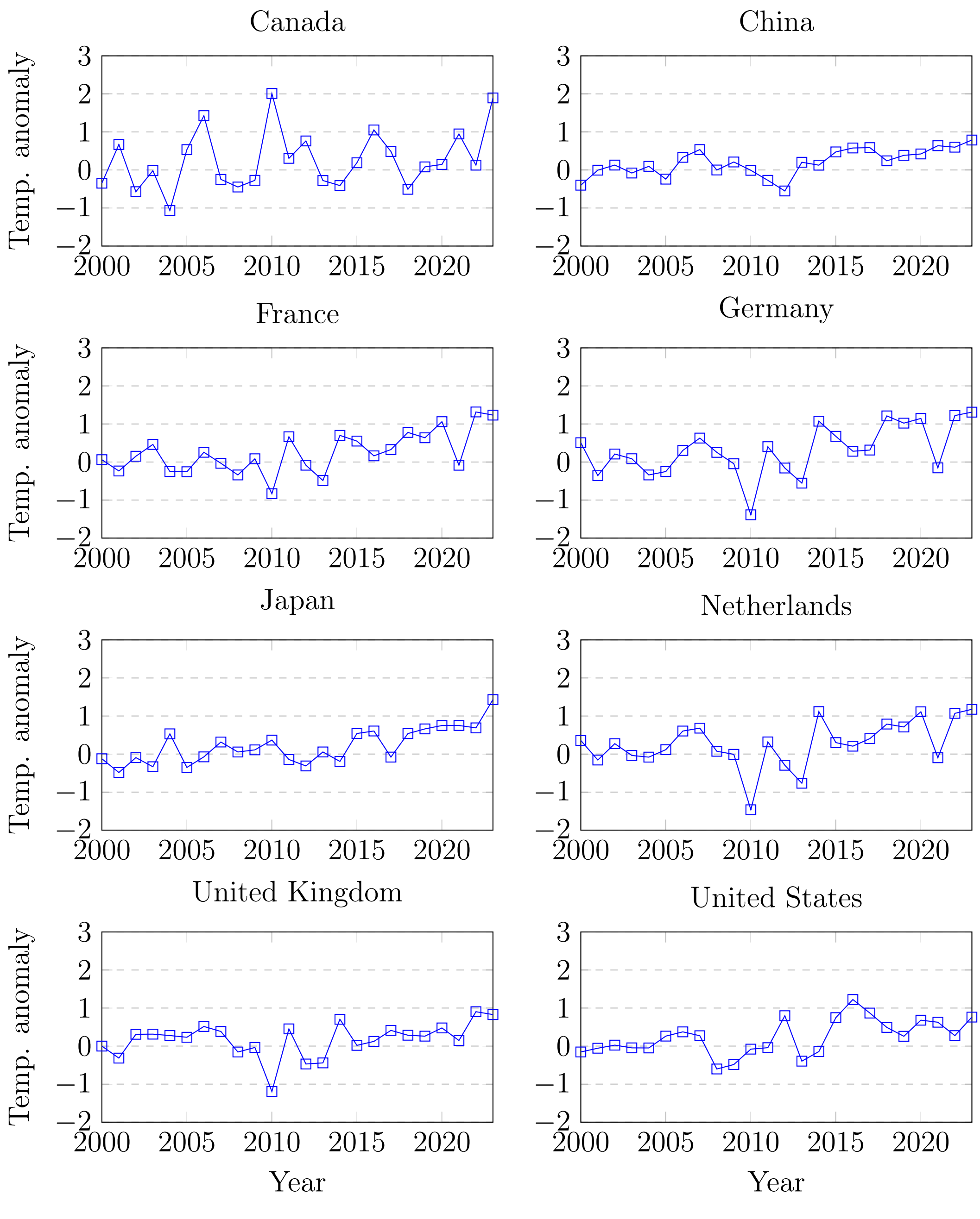
structure needs to be adjusted to maintain the intended economic impact. For instance, a temperature anomaly in Fahrenheit will not be directly equivalent to the same numerical value in Celsius, so the conversion must be factored in. Second, climate-linked bonds will include provisions to ensure that coupons or redemption values cannot be negative. This is a crucial feature to protect investors and maintain the bond's value. If the temperature-based pay-off calculation could potentially lead to negative values, the bond's structure must incorporate mechanisms to ensure that such values are not realized.

D CO_2-trajectories

Figure 7 illustrates the annual CO_2-trajectories for major economies, highlighting deviations from the 1991-2020 average CO_2 emissions from fossil fuels and industry, excluding land-use changes. Each subfigure represents a different country, including Canada, China, France, Germany, Japan, the Netherlands, the United Kingdom, and the United States, covering the period from 2000 to 2023.

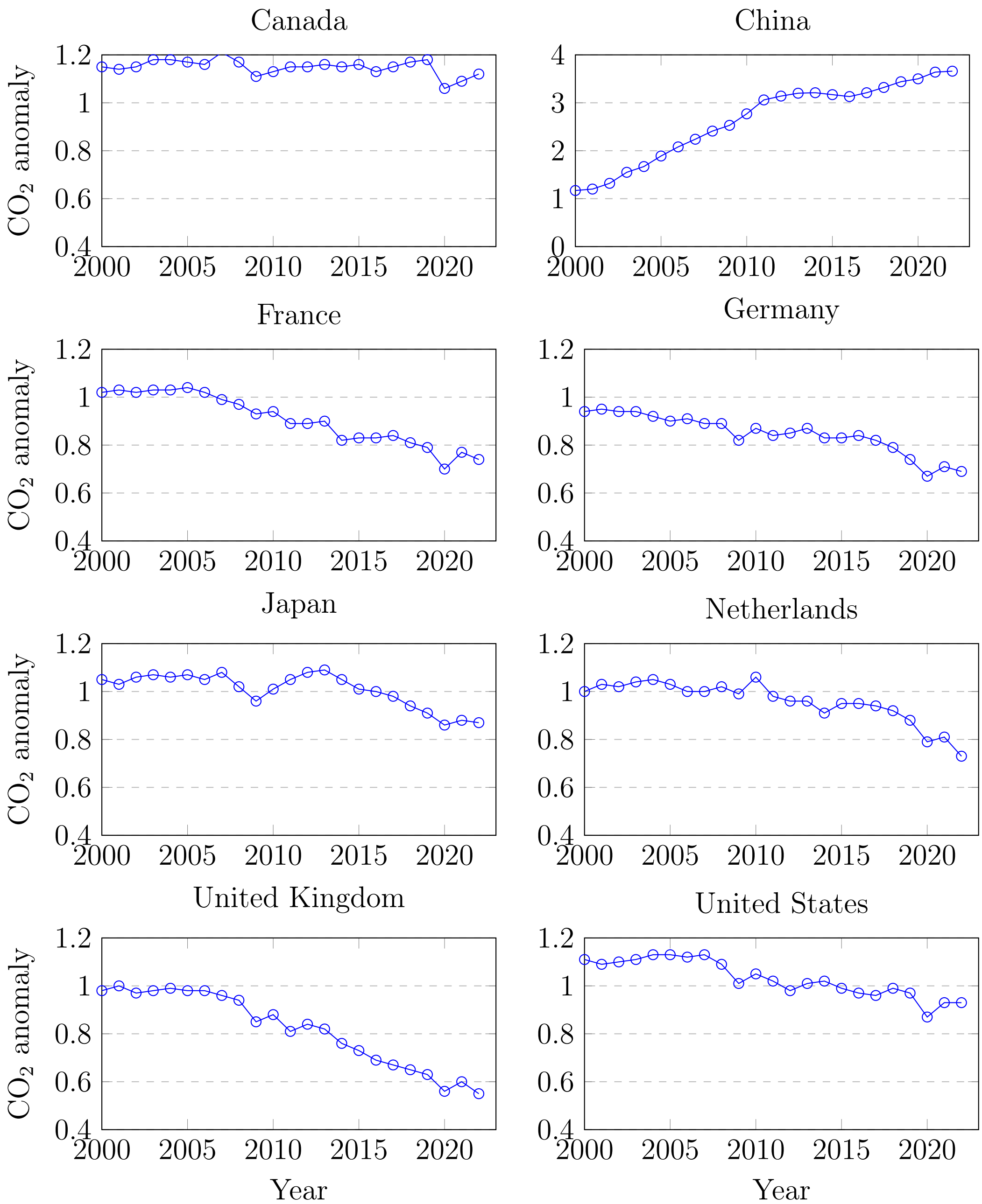
China's CO_2-trajectory shows a significant upward trend, with emissions rising sharply over the period, reflecting the country's rapid industrial growth. In contrast, the trajectories for Canada, France, Germany, Japan, the Netherlands, the United Kingdom, and the United States show relatively stable to downward trends, with some annual fluctuations that could be reflected in the payoff structure of climate-linked bonds.

Figure 6: Temperature anomalies for major economies



Note. This figure shows the annual temperature anomalies for large economies since 2000, indicating deviations from the 1991-2020 average surface temperature in degrees Celsius. The source includes modified information from the Copernicus Climate Change Service. Source: `https://ourworldindata.org/grapher/annual-temperature-anomalies`.

Figure 7: CO_2-trajectories for major economies



Note. This figure shows the annual CO_2-trajectories for large economies since 2000, indicating deviations from the 1991-2020 average CO_2 emissions from fossil fuels and industry. Land-use change is not included. Source: `https://ourworldindata.org/co2-dataset-sources`.