Climate-Linked Bonds*

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Introduction

- Climate change presents urgent and potentially irreversible risks (IPCC, 2023).
- No trade-off: Any delay in mitigation increases *both* physical and transitional risks.
- Internalizing climate externalities via carbon taxes is most effective (Pedersen, 2023).
- Climate-linked bonds serve as a policy tool to signal commitment and align incentives.

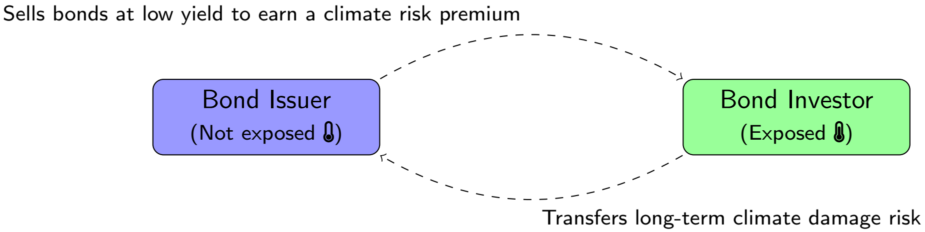
What are climate-linked bonds?

- Debt instruments with pay-offs that adjust based on *realized* climate-related metrics.
- Similar in structure to inflation-linked bonds, but tied to a climate variable instead.
- For example, average land temperature, greenhouse gas concentration levels.
- Provide government funding while attracting climate-conscious hedgers.

Climate-linked bonds and market incompleteness

- Financial markets lack instruments allowing investors to hedge climate risk effectively.
- Several papers propose hedging strategies using asset price sensitivity to climate news (Andersson et al., 2016; De Jong and Nguyen, 2016; Engle et al., 2020).
- Such dynamic strategies provide imperfect hedges and incur high transaction costs.
- Climate-linked bonds feature an adjustment mechanism for direct risk hedging.

Main idea behind climate-linked bonds



- In equilibrium agents agree on the quantity and price of climate-linked bonds.
- Agents could trade directly, but the government facilitates the risk-sharing.
- Climate-linked bonds differ significantly from catastrophe bonds:
  - In case of climate-linked bonds the protection is for the investor, not the issuer.
  - Protection runs via the link of the climate variable to long-term damages.
  - Coupons adjust at discrete times without a specific trigger event.

Comparison of climate-linked to related bonds

Bond Type	Use of Proceeds	Pay-off Structure	Main Issuers
Climate-linked bonds	General financing and green projects	Linked to climate variable	Governments and supra-nationals
Green bonds	Green projects	Regular fixed or floating coupon	Governments and companies
Sustainability-linked bonds	General financing	Linked to self-imposed targets	Governments and companies
Catastrophe bonds	Placed in SPV for risk transfer	Linked to catastrophe	Insurance and reinsurance firms

Climate-linked bonds reduce three gaps

1. **Information gap**
    - Trading and pricing of climate risk enhance risk sharing and transparency.
    - Reveals the market-consistent climate risk premium.
2. **Incentive gap**
    - Governments benefit financially from effective long-term climate policies.
    - Can serve as a step toward forming a “climate club” (Nordhaus, 2015).
3. **Insurance gap**
    - Provides investors with a direct hedge against long-term climate risks.
    - Complements traditional insurance mechanisms (ECB & EIOPA, 2024).

Benefits of climate-linked bonds

For governments:

- Align financial obligations with climate action, internalizing climate externalities.
- Benefit from lower yields and potential price premium (*greenium*).
- Increase transparency and accountability in climate policy.

For investors:

- Climate-linked bonds provide a hedge against long-term climate risks.
- Diversification benefits from low bond-business cycle correlation.

For financial markets and the economy in general:

- Contribute to completing markets by creating an instrument to trade climate risk.
- Improve the accuracy and efficiency of price discovery for climate-related risks.

Pricing climate-linked bonds

Closed economy:

- All agents in the economy have CARA utility with risk aversion coefficient α.
- Exposed agents (δ share) suffer climate damages and demand the bonds.
- Unexposed agents ($1-\delta$ share) supply the bonds.

Climate dynamics and damages:

- Temperature anomalies: $\Delta T \sim N(\mu, \sigma^2)$.
- Climate damages: $D_{\tau+1} = d_0 + d_1 \Delta T + \varepsilon_{\tau+1}$, with damage sensitivity $d_1 > 0$.

Agents optimize their asset allocation:

- Risk-free bond with fixed return R_f.
- Climate-linked bond with return $B_{\tau+1} = b_0 + b_1 \Delta T$.
- Agents maximize the expected utility of final wealth, net of climate damages.

Market clearing and equilibrium price

Optimal bond holdings are driven by two components:

- An investment demand driven by risk aversion and the Sharpe ratio of the bonds.
- A hedging demand proportional to the bond's sensitivity to climate change.

Market equilibrium:

- The net supply of climate-linked bonds is zero.
- Market clearing condition: $\delta\theta^e_\tau + (1-\delta)\theta^u_\tau = 0$.
- Equilibrium bond price:

$$B_\tau = \underbrace{R_f^{-1}\mathbb{E}(B_{\tau+1})}_{\text{Expected Disc. Payoff}} + \underbrace{R_f^{-1}\alpha\delta\mathbb{C}\mathrm{ov}(B_{\tau+1}, D_{\tau+1})}_{\text{Climate Risk Premium}}. \tag{1}$$

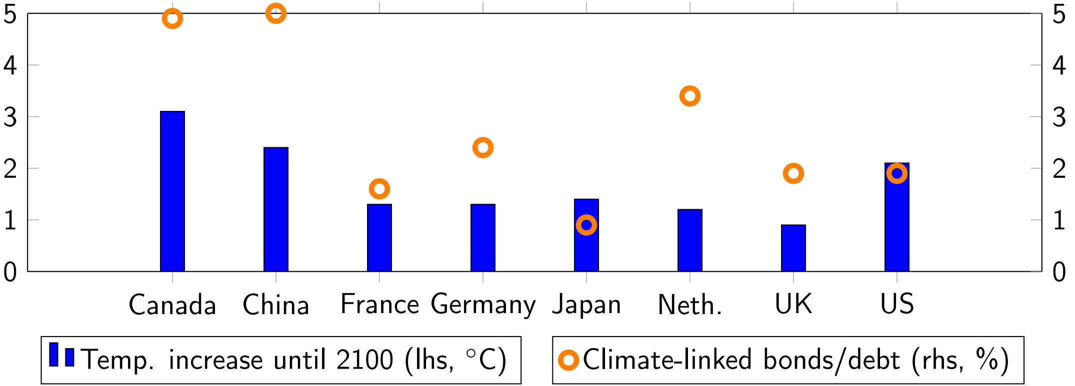
How much climate-linked bonds to issue?

- Climate-linked bonds to replace some conventional bonds in a country's nominal debt.
- Assume the outstanding amount f (as a % of GDP) is issued to cover expected annual damages over a h=75-year horizon, with $1/m$ of the bonds redeemed annually.

$$\underbrace{d_1 \frac{\mu}{h}}_{\text{Expected Damage}} = \underbrace{b_1 \frac{\mu}{h} f + \frac{1}{m} f}_{\text{Coupon Adj. and Bond Redemption}} \quad \Rightarrow \quad f = \frac{d_1 \mu / h}{b_1 \mu / h + \frac{1}{m}}. \tag{2}$$

- Damage sensitivity to temperature increase: $d_1 = .12$ (Bilal and Känzig, 2024).
- Expected temperature increase per country from Berkeley Earth.

Expected temperature increase vs bond issuance



Note: The share is 2-3 times larger if governments cover 2 st. dev. of temperature variation $\sigma_{\Delta T} = 1.1$°C.

Political aspects of climate bond issuance

Challenges:

- Strategic use of debt to constrain future governments (Alesina and Tabellini, 1990).
- Free-riding concerns due to partial government control over climate variables.
- Long transmission lag between climate policies and observable effects.

Counterarguments:

- Institutional settings can enhance policy enforcement, climate clubs (Nordhaus, 2015).
- Effectiveness increases when more governments or supernationals issue the bonds.
- Bonds with varying maturities distribute financial impacts across political terms.
- Immediate feedback from market pricing enhances credibility and commitment.

Conclusion

Key message: Climate-linked bonds help to prepare for extreme events:

- **Incentivizing Policy Action:** Governments get fiscal incentive for climate mitigation.
- **Hedging Climate Risk:** Investors mitigate exposures to long-term climate damages.
- **Reducing the Insurance Gap:** Formalizes government role as insurer of last resort.
- **Enhancing Price Discovery:** Term structure of the climate risk premium.

Paper link

For more details, see the full paper on SSRN:

Climate-Linked Bonds

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Appendix: Asset pricing model

Modeling the pricing of climate-linked bonds

To explore the risk-sharing and pricing aspects of the bonds we go through four steps:

- A stylized setting of a closed economy with two types of risk-averse agents.
- A model for temperature anomaly dynamics and climate-related damages.
- Asset allocation of agents with risk-free and climate-linked bonds.
- Market clearing and the equilibrium bond price.

Stylized economy with (un)exposed agents

- A closed economy with two types of risk-averse agents ($i = e, u$):
  - **Exposed (e)**: A δ share of the population that directly suffers climate damages.
  - **Unexposed (u)**: The remaining $1 - \delta$ share, is less or not affected by climate damages.
- Exposed agents demand climate-linked bonds, while unexposed agents supply them.
- All agents have CARA utility, with risk aversion coefficient α:

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

Climate dynamics and related damages

- Temperature anomalies are measures as deviations from some reference level:

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

- Agents are exposed to climate-related damages that are modeled as:

$$D_{\tau+1} = d_0 + d_1 \Delta T + \epsilon_{\tau+1}, \quad \epsilon_{\tau+1} \sim N(0, \sigma_{d,\epsilon}). \tag{5}$$

- Parameter $d_1 > 0$ represents the sensitivity of damages to temperature anomalies.

Assets and investment decision process

- Agents allocate their initial wealth endowment y_τ between:
  - A risk-free bond, which pays a fixed return R_f at maturity.
  - A risky climate-linked bond, with a payoff dependent on temperature anomaly:

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

- Let θ^i_τ denote the time τ number of climate-linked bonds purchased by type i agents.
- Agents maximize the expected utility of final wealth, net of climate damages:

$$\max_{\theta^i} \mathbb{E}\left[u\left(\underbrace{\theta^i_\tau B_{\tau+1}}_{\text{CLB Payoff}} + \underbrace{(y_\tau - \theta^i_\tau B_\tau) R_f}_{\text{Risk-Free Bond Payoff}} - \underbrace{D_{\tau+1} 1_i}_{\text{Climate Damages}} \right) \right].$$

Optimal bond holdings

- First-order condition for optimal bond holdings:

$$\theta^i_\tau = \underbrace{\frac{1}{\alpha\sqrt{\mathbb{Var}(B_{\tau+1})}} SR(B_{\tau+1})}_{\textbf{Investment Demand } \theta^i_{ID}} + \mathbb{1}_i \cdot \underbrace{\frac{\mathbb{Cov}(D_{\tau+1}, \Delta T_{\tau+1})}{\mathbb{Cov}(B_{\tau+1}, \Delta T_{\tau+1})}}_{\textbf{Hedging Demand } \theta^e_{HD}}. \qquad (6)$$

- Demand splits into:
  - Investment demand driven by risk aversion and climate-linked bonds' Sharpe ratio.
  - Hedging demand proportional to bond sensitivity to damages.
- Idiosyncratic damage risk, $\epsilon_{\tau+1}$, does not impact allocation and hedging demand.

Market clearing and equilibrium bond price

- In equilibrium the net supply of climate-linked bond is zero.
- To clear the market, the supply of climate-linked bonds must equal the demand:

$$\delta\theta^{e}_{\tau} + (1-\delta)\theta^{u}_{\tau} = 0. \tag{7}$$

- Solving for equilibrium bond price:

$$B_{\tau} = \underbrace{R_f^{-1}\mathbb{E}(B_{\tau+1})}_{\text{Expected Disc. Payoff}} + \underbrace{R_f^{-1}\alpha\delta\mathbb{C}\mathbb{o}\mathbb{v}(B_{\tau+1}, D_{\tau+1})}_{\text{Climate Risk Premium}}. \tag{8}$$

Hedging demand and hedging supply

- Rearrange the market-clearing condition to get aggregate demand and supply:

$$\begin{aligned} \delta(\theta^e_{ID} + \theta^e_{HD}) + (1-\delta)\theta^u_{ID} &= 0 \\ \iff \underbrace{\delta\theta^e_{HD}}_{\text{Hedging demand}} &= \underbrace{-\theta^u_{ID}}_{\text{Hedging supply}} . \end{aligned} \tag{9}$$

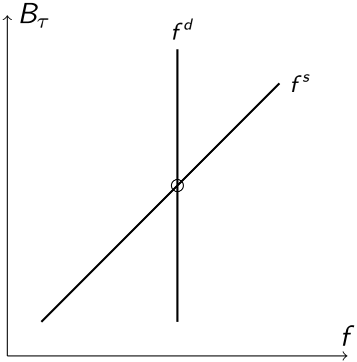
- Demand is driven by the correlation between the climate-linked bonds payoff and the climate damages of the exposed agents:

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

- Supply is driven by the willingness of agents to issue climate-linked bonds at higher price than the risk-free asset:

$$f^s \equiv -\theta^i_{ID} = \frac{R_f B_\tau - (b_0 + b_1\mu)}{\alpha\sigma^2 b_1^2}$$

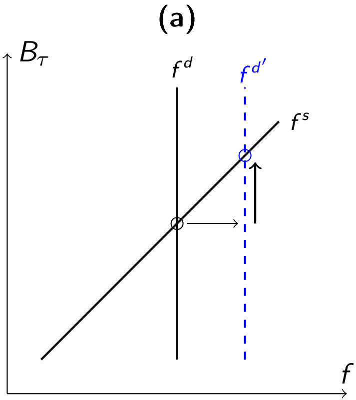
Demand meets supply of the bonds

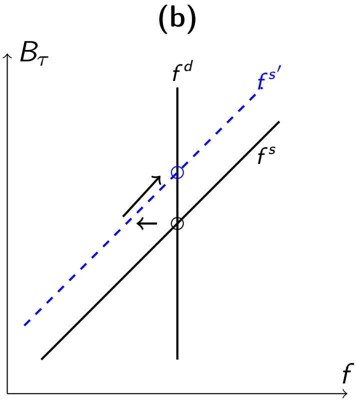


Intuition:

- Price-inelastic demand (f^d): depends on the share of exposed agents, and the bond payoff correlation to climate damages.
- Price-elastic supply (f^s) depends on the level of the risk premium.

Market dynamics





- **(a)**: More exposed agents shifts hedging demand, increasing price and issuance.
- **(b)**: Higher expected temp. anomaly shifts supply, raising bond price to rebalance.

Completing the market

- Given the prices of the risk-free bond and the climate-linked bond, a unique Stochastic Discount Factor (SDF) exists

$$
\begin{aligned}
E(R_f M_{\tau+1}) &= 1, \\
E(B_{\tau+1} M_{\tau+1}) &= B_\tau
\end{aligned}
\tag{10}
$$

- Derive the SDF: $M_{\tau+1} = m_0 + m_1 \Delta T$ and use it to price any climate-related financial payoff
- Call option on temperature $C_{\tau+1} = \max(T_{\tau+1} - T^s, 0)$ implies

$$
C_\tau = \mathbb{E}\left(M_{\tau+1} C_{\tau+1}\right) = \frac{1}{R_f} \Phi\left(\frac{\mu - (T^s - \overline{T})}{\sigma}\right)\left(\mu + d_1 \delta \alpha \sigma^2 - (T^s - \overline{T})\right). \tag{11}
$$