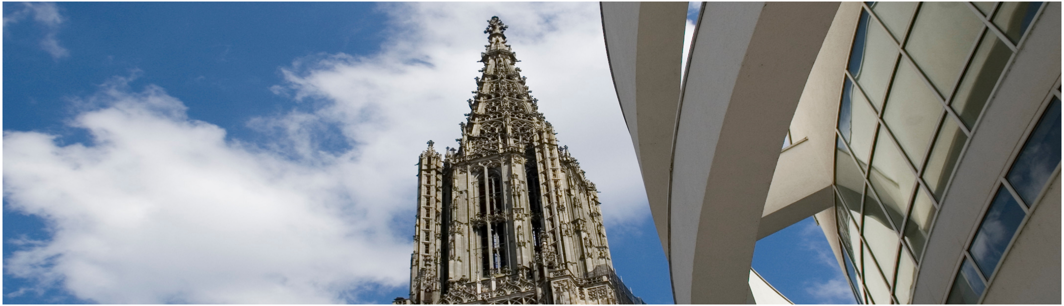

Sustainability-Linked Debt, Capital Structure, and Endogenous Default

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Sustainability-linked bonds (SLBs): Motivation & Importance

- A lot of financial instruments have emerged to promote environmentally friendly and sustainable initiatives
  - First green bond: European Investment Bank, 2007
  - Recent addition: sustainability-linked bonds (SLBs); first SLB by Enel in 2019
- **Cash-flow linkage** of SLB
  - Bond's coupons tied to sustainability performance targets (SPTs) tracked by key performance indicators (KPIs)
- **Common features**
  - Rewards meeting (or over-achieving) sustainability performance targets
  - Penalizes under-performance $\Rightarrow$ coupon *step-up* penalty if sustainability performance targets are not achieved

An Example of an SLB: Deutsche Post AG (ISIN XXS2644423035)

- Bond issued in June 2023, maturing in 2033
    - Regular coupon 3.375%
    - Performance examination date: December 2030
    - Key performance indicators (KPI):
        - KPI 1: GHG Emissions (Scope 1 + Scope 2)
        - KPI 2: GHG Emissions (Scope 3)
    - Sustainability performance target (SPT):
        - 42% reduction from 2021 to performance examination date for KPI 1
        - 25% reduction from 2021 to performance examination date for KPI 2

        → penalty coupon step up: +0.25% from 2031 to 2033 if one or two targets are missed or KPI is not reported

What We Do in This Paper

- Traditional capital structure theory (e.g., structural credit frameworks of Black and Cox (1976) and Leland (1994)) weighs coupon tax shields of debt against bankruptcy costs
- We extend this stream of literature to a perpetual sustainability-linked bond (SLB) setting
- Penalty-linked coupons affect both debt burden and tax shields
- We study endogenous default boundary and optimal capital structure
- Compare SLB to an otherwise identical conventional bond baseline

Key Results: SLB vs. Conventional Bond

- Enhancement of Overall Firm Value through two Channels
  - *Longer-Term Default Strategy*: Equity value can be held constant, then SLB allow for a lower bankruptcy threshold
  - *Higher Debt Capacity*: The optimal SLB policy implies a markedly more levered capital structure
- Optimal Financing
  - If the SLB is structured properly, *total firm value* strictly exceeds the conventional bond benchmark
- Robustness in the Presence of Carbon Pricing
  - In the extended model, we show that our results also hold if carbon taxation is added to the baseline model

Contribution to the Literature

- First structural model that endogenizes default while embedding *continuous* ESG penalties
- Shows how optimal leverage responds to design of SLB contract terms
- Extends empirical findings on SLB "greenium" (Feldhütter et al., 2024; Mariani et al., 2025; Kölbel and Lambillon, 2022) with a tractable infinite-horizon theory
- Differs from discrete-horizon contract-design papers (Allen et al., 2023; Barbalau and Zeni, 2022) by focusing on closed-form valuation and capital-structure trade-offs

Road Map

- Introduction and motivation $\surd$
- Model in a nutshell: debt and equity valuation
- Analytical results and numerical illustrations
- Concluding remarks

Model Ingredients I
Capital Structure & SLB Contract

- Capital Providers
  - Equity: residual claim, junior at default
  - SLB: senior claim with sustainability-linked features
- SLB Cash Flows
  - Base coupon c_0 paid continuously
  - Penalty step-up Δc if emissions I_t exceed threshold I_B
  - Recovery at default: $(1 - \alpha_D)V_B$

Model Ingredients II
State-Variable Dynamics

- Asset Value (risk–neutral measure $\mathbb{Q}$)

$$dV_t = r\,V_t\,dt + \sigma\,V_t\,dW_t^{\mathbb{Q}}$$

- Emission Level, KPI

$$I_t = I_0(1 - \alpha^{\mathbb{Q}} t) + \sigma_I W_t^{I,\mathbb{Q}}, \quad \operatorname{corr}(dW_t^{\mathbb{Q}}, dW_t^{I,\mathbb{Q}}) = \rho dt$$

  - $\alpha^{\mathbb{Q}}$: adjusted drift rate under $\mathbb{Q}$
  - Correlation ρ captures co-movement of financial performance and emissions
- SLB payments: $c_0 + \Delta c\,\mathbb{1}_{\{I_u > I_B\}}$ given no default

Model Ingredients III
Default, Recovery, Valuation Targets

- Default Trigger:

$$\tau = \inf\{t \geq 0 : V_t \leq V_B\}$$

- Bankruptcy threshold V_B *exogenous* (regulatory) or *endogenous* (chosen by equity holders)
- Pay-off at Default:

$$\text{SLB recovery} = (1 - \alpha_D)V_B, \qquad \text{Equity} = 0$$

SLB Valuation: Expected Discounted Cash Flows

$$
\begin{aligned}
&D(t, V_t, V_B, c_0, I_t, \Delta c) \\
=&\mathbb{E}^{\mathbb{Q}}\Big[\int_t^{\tau} e^{-r(u-t)}\big(c_0 + \Delta c\,\mathbb{1}_{\{I_u > I_B\}}\big)\,du \;+\; e^{-r(\tau-t)}(1-\alpha_D)V_\tau \;\Big|\; V_t, I_t\Big], \\
&\tau = \inf\{u > t : V_u \le V_B\}
\end{aligned}
$$

- Base coupon c_0
  - Continuous payment while firm is solvent
  - Discounted at risk-free rate, weighted by survival probability
- Emission penalty $\Delta c\,\mathbb{1}_{\{I_u > I_B\}}$
  - Coupon *step-up* whenever emissions exceed threshold I_B
  - Encodes incentive to reduce carbon footprint via higher financing cost
- Recovery at default $(1-\alpha_D)V_\tau$
  - Paid when $V_\tau = V_B$ is hit
  - α_D captures bankruptcy/resolution costs; equity is wiped out

Equity Valuation: Beyond the Classical Trade-Off

$$
\begin{aligned}
E(t, V_t, V_B, c_0, I_t, \Delta c) =& V_t - D(t, V_t, V_B, c_0, I_t, \Delta c) \\
&+ \mathbb{E}^{\mathbb{Q}}\left[\int_t^{\tau} e^{-r(u-t)}\, \tilde{\tau}\, \big(c_0 + \Delta c\, \mathbb{1}_{\{I_u > I_B\}}\big)\, du \;\Big|\; V_t, I_t\right] \\
&- \mathbb{E}^{\mathbb{Q}}\big[e^{-r(\tau-t)} \alpha_D V_\tau \;\big|\; V_t, I_t\big],
\end{aligned}
$$

$$
\tau = \inf\{u > t : V_u \le V_B\}, \quad E(\tau, \cdot) = 0
$$

- From Classical to Sustainability-Linked Trade-Off
  - Traditional capital structure theory weighs coupon tax shields of debt against bankruptcy costs
  - Our model introduces a new channel: Penalty-linked coupons affect both debt burden and tax shields
  - Equity value now reflects not only financial leverage, but also environmental performance

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Endogenous Default

- Equity holders choose the default threshold such that the equity value is maximized (endogenous default)
- The *optimal default threshold* V_B^* is defined via

$$V_B^* = \underset{V_B \in [0, V_0]}{\arg\max}\ E(0, V_0, V_B, c_0, I_0, \Delta c).$$

- Concavity of the equity value in V_B and maximization over a compact interval ensure existence and uniqueness of V_B^*

Notions for Analysis

- Specified notation:

$$V_B^*(c_0, \Delta c): \text{ Optimal bankruptcy threshold given } c_0 \text{ and } \Delta c$$
$$E(V_B, c_0, \Delta c) := E(0, V_0, V_B, c_0, I_0, \Delta c)$$
$$D(V_B, c_0, \Delta c) := D(0, V_0, V_B, c_0, I_0, \Delta c)$$

- Total firm value:

$$TFV(V_B, c_0, \Delta c) := E(V_B, c_0, \Delta c) + D(V_B, c_0, \Delta c)$$

- Debt configurations:

$$(c_0^{\text{con}}, 0): \text{ Conventional debt}, \qquad (c_0^{\text{slb}}, \Delta c): \text{ SLB debt}$$

- Given a $c_0^{\text{con}} > 0$, we say SLB debt is *value enhancing* if there exists a configuration $(c_0^{\text{slb}}, \Delta c)$ such that the following holds:

$$TFV(V_B^*(c_0^{\text{con}}, 0), c_0^{\text{con}}, 0) < TFV\left(V_B^*\left(c_0^{\text{slb}}, \Delta c\right), c_0^{\text{slb}}, \Delta c\right)$$

Analytical Results I (Equity Matching)

Proposition

Let $c_0^{\text{con}} > 0$ be fixed. Assume that an SLB debt configuration $(c_0^{\text{slb}}, \Delta c^{\text{eq}})$ exists such that the optimal equity values match, i.e.,

$$E(V_B^*\left(c_0^{\text{slb}}, \Delta c^{\text{eq}}\right), c_0^{\text{slb}}, \Delta c^{\text{eq}}) = E(V_B^*\left(c_0^{\text{con}}, 0\right), c_0^{\text{con}}, 0),$$

and that the corresponding optimal bankruptcy threshold for SLB debt is lower:

$$V_B^*\left(c_0^{\text{slb}}, \Delta c^{\text{eq}}\right) < V_B^*\left(c_0^{\text{con}}, 0\right).$$

Then SLB debt is value enhancing, i.e., it holds:

$$TFV(V_B^*\left(c_0^{\text{con}}, 0\right), c_0^{\text{con}}, 0) < TFV(V_B^*\left(c_0^{\text{slb}}, \Delta c^{\text{eq}}\right), c_0^{\text{slb}}, \Delta c^{\text{eq}}).$$

Analytical Results II (Equity Matching)

Theorem

Let $c_0^{\text{con}} > 0$ be fixed, $\rho = 0$, $I_0 \geq I_B$ and $\alpha^{\mathbb{Q}} \geq 0$. Then SLB debt is value enhancing.

The assumptions are mild:

- $I_0 \geq I_B$: Firm has an SPT below the current emission level
- $\alpha^{\mathbb{Q}} \geq 0$: Firm actually intends to reduce its emissions
- $\rho = 0$: Ensures analytical tractability (numerics show that it is not a necessary condition)

$\Rightarrow$ First channel: Equity matching is quite restrictive (from equity holders' point of view), but is already value enhancing

Analytical Results III (Optimal Financing)

Optimal Financing:

- Debt configuration is chosen such that total firm value is maximized
- Taking into account that bankruptcy threshold is chosen optimally by equity holders
- Optimization problem (conventional debt):

$$\max_{c_0^{\text{con}} \geq 0} \left\{ E(V_B^* \left(c_0^{\text{con}}, 0\right), c_0^{\text{con}}, 0) + D(V_B^* \left(c_0^{\text{con}}, 0\right), c_0^{\text{con}}, 0) \right\}$$

- Resulting optimal coupon payment ${c_0^*}^{\text{con}}$:

$${c_0^*}^{\text{con}} = \underset{c_0^{\text{con}} \geq 0}{\operatorname{argmax}} \left\{ E(V_B^* \left(c_0^{\text{con}}, 0\right), c_0^{\text{con}}, 0) + D(V_B^* \left(c_0^{\text{con}}, 0\right), c_0^{\text{con}}, 0) \right\}$$

Analytical Results IV (Optimal Financing)

- Optimization problem (SLB debt, $0 \leq c_0^{\text{slb}} < c_0^{\text{con}}$ fixed):

$$\sup_{\Delta c > 0} \{E(V_B^* \left(c_0^{\text{slb}}, \Delta c\right), c_0^{\text{slb}}, \Delta c) + D(V_B^* \left(c_0^{\text{slb}}, \Delta c\right), c_0^{\text{slb}}, \Delta c)\}$$

- Δc^* (if exists): Optimal penalty coupon payment

Corollary

Let $\rho = 0$, $I_0 \geq I_B$, *and* $\alpha^{\mathbb{Q}} \geq 0$. *For any* $0 \leq c_0^{\text{slb}} < c_0^{*\text{con}}$,

$$TFV\left(V_B^*(c_0^{*\text{con}}, 0)\right), c_0^{*\text{con}}, 0) < TFV(V_B^*\left(c_0^{\text{slb}}, \Delta c^*\right), c_0^{\text{slb}}, \Delta c^*).$$

$\Rightarrow$ Second channel: Global optimal SLB configuration is value enhancing (though equity value might be lower)

Base Case Parameters

Parameter	Value	Parameter	Value	Parameter	Value
V_0	100	$\tilde{\tau}$	0.25	ρ	0
σ	0.3	α_D	0.25	I_B	7.5
r	0.04	I_0	15	θ_1	0.04
c_0	3	α^*	0.05	θ_2	0.02
Δc	1.5	σ_I	0.25		

Table: Base case parameters

Illustration of Equity Matching

$\alpha^{\mathbb{Q}}$	0.2	0.05	0	-
c_0^{slb}	4	4	4	5
Δc^{eq}	5.92	1.97	1	-
$V_B^*\left(c_0^{\text{slb}}, \Delta c^{\text{eq}}\right)$	35.96	40.74	44.12	44.12
$E(V_B^*\left(c_0^{\text{slb}}, \Delta c^{\text{eq}}\right), c_0^{\text{slb}}, \Delta c^{\text{eq}})$	30.23	30.23	30.23	30.23
$D(V_B^*\left(c_0^{\text{slb}}, \Delta c^{\text{eq}}\right), c_0^{\text{slb}}, \Delta c^{\text{eq}})$	84.57	82.33	80.59	80.59
$TFV(V_B^*\left(c_0^{\text{slb}}, \Delta c^{\text{eq}}\right), c_0^{\text{slb}}, \Delta c^{\text{eq}})$	114.8	112.56	110.82	110.82

Table: Illustration of the main results. The SLB is value enhancing if $\alpha^{\mathbb{Q}} \geq 0$. Note that $TFV(V_B^*\left(c_0^{\text{slb}}, \Delta c^{\text{eq}}\right) c_0^{\text{slb}}, \Delta c^{\text{eq}})$ is just the total firm value of the firm for the matched equity constraint and not the overall best SLB configuration with c_0^{slb} as base coupon. The right column corresponds to the conventional debt case with $c_0^{\text{con}} = 5$.

Equity Matching vs. Optimal Financing

Optimal Financing		Equity Matching	
Δc^*	4.43	Δc^{eq}	2.00
$V_B^*\left(c_0^{\text{slb}}, \Delta c^*\right)$	37.66	$V_B^*\left(c_0^{\text{slb}}, \Delta c^{\text{eq}}\right)$	30.33
$E(V_B^*\left(c_0^{\text{slb}}, \Delta c^*\right), c_0^{\text{slb}}, \Delta c^*)$	27.91	$E(V_B^*\left(c_0^{\text{slb}}, \Delta c^{\text{eq}}\right), c_0^{\text{slb}}, \Delta c^{\text{eq}})$	41.36
$D(V_B^*\left(c_0^{\text{slb}}, \Delta c^*\right), c_0^{\text{slb}}, \Delta c^*)$	86.90	$D(V_B^*\left(c_0^{\text{slb}}, \Delta c^{\text{eq}}\right), c_0^{\text{slb}}, \Delta c^{\text{eq}})$	72.05
$TFV(V_B^*\left(c_0^{\text{slb}}, \Delta c^*\right), c_0^{\text{slb}}, \Delta c^*)$	114.81	$TFV(V_B^*\left(c_0^{\text{slb}}, \Delta c^{\text{eq}}\right), c_0^{\text{slb}}, \Delta c^{\text{eq}})$	113.41

Table: Illustration of the optimal financing case. If $\alpha^{\mathbb{Q}} \geq 0$ and $I_0 > I_B$, the total firm value in the optimal financing case is higher for SLB debt for every choice of $0 \leq c_0^{\text{slb}} < c_0^{*^{\text{con}}}$. We fix $c_0^{\text{slb}} = 3$ and compare the optimal financing case with the equity matching case. Reference values for the optimal conventional debt configuration: $c_0^{*^{\text{con}}} = 3.94$, $V_B^*\left(c_0^{*^{\text{con}}}, 0\right) = 34.80$, $E(V_B^*\left(c_0^{*^{\text{con}}}, 0\right), c_0^{*^{\text{con}}}, 0) = 41.37$, $D(V_B^*\left(c_0^{*^{\text{con}}}, 0\right), c_0^{*^{\text{con}}}, 0) = 70.23$, $TFV(V_B^*\left(c_0^{*^{\text{con}}}, 0\right), c_0^{*^{\text{con}}}, 0) = 111.60$.

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Take-Aways: Key Results

- Enhancement of Overall Firm Value through two Channels
  - *Longer-Term Default Strategy*: Equity value can be held constant, then SLB allow for a lower bankruptcy threshold
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Thank you very much for your attention!

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