Climate credit risk and corporate valuation

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This paper in a nutshell

- CLIMACRED model for climate scenario-contingent valuation, linking firm's default probability (PD) to climate scenarios (NGFS)
- Changes in expectations about materialization of climate policy scenarios lead to adjustments in firms' PD and bond value
- Closed-form expressions for the adjustments in firms' PD and value of issued bonds: analytical solutions supported by empirical results
- Revenues shares from energy technologies evolve dynamically, coherently with the scenario
- Applications in supervisory climate stress-test, e.g. Swiss National Bank, Monetary Authority of Singapore, Banco de Mexico, NGFS.

Motivation: climate risk challenges traditional financial valuation and risk assessment

- **Climate risk brings about a new type of financial risk** [Battiston ea. 2017 NCC; NGFS 2019, IPCC AR6 2022]:
  - Endogeneity: decision makers' perception of climate risks impacts its materialisation by affecting policy and investment decisions
  - Deep uncertainty, non-linearity of climate impacts and tipping points (irreversibility) [Steffen ea 2018; Lenton ea 2019]
- **Standard approaches to financial valuation and risk management are not adequate** [Battiston 2019 BdF]:
  - Based on past data (e.g. reported emissions, announcements)
  - But with climate, statistical properties of the future differ from the past: less relevant to estimate coeffiecients based on past info
  - Stress-test rely on short-term scenarios vs long-term climate impacts
  - Incomplete markets (e.g. insurance) limit hedging strategies.

Motivation: climate scenarios-contingent valuation

- Forward-looking dimension of risk: need to work with scenarios
- Climate scenarios for financial risk assessment are developed by the Network for Greening the Financial System (NGFS)

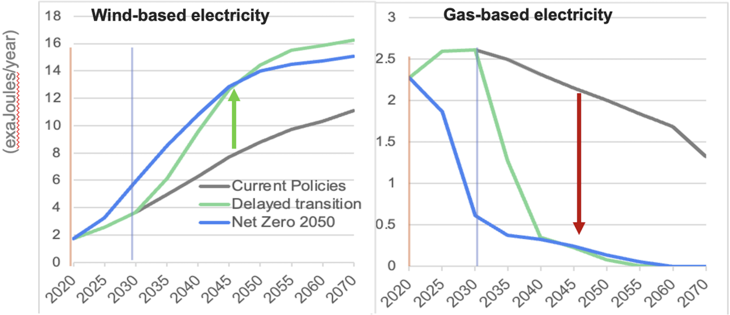

Figure: Output trajectories (wind, coal) across 3 scenarios (CurrPolicies, Delayed Transition, NetZero2050) for the EU, 2020-2070, under model REMIND-Mag-Pie. Source: NGFS 2022.

Motivation: climate scenarios-contingent valuation

- Trajectories of future cash flows may depend on climate scenarios:
    - 2C scenario: output and cash flows of fossil firms due to drop vs business-as-usual scenario
    - However, output and cash flows of low-carbon firms (e.g. electricity/wind) expected to increase
- Lack of a credible carbon price signal (Stiglitz, 2016) contributes to ambiguity (Berger ea. 2017; Hansen and Miao 2022) on expectations' about the realization of mitigation scenarios
- Probabilities of scenarios are difficult to determine because of the endogeneity of climate risk (Battiston ea. 2021)
- Ambiguity and endogeneity of scenarios motivates further the idea to carry out a scenario-contingent valuation (e.g. NGFS).

Related work: climate financial risk literature

Climate financial risk

- Battiston ea. (2017)'s Climate Stress-test: first work to establish the use of climate transition scenarios to adjust financial valuation of securities and risk measures (transition risk)
- Monasterolo ea. (2018): credit portfolios of Chinese development banks in energy projects loans
- Roncoroni ea. (2021): systemic effects in networks of banks and investment funds, arising from portfolios overlap (Banco de Mexico)
- Battiston ea. (2021): endogeneity of climate risk. Scenario trajectories affected by investors' expectations about policy cedibility
- Bressan ea. (2023): Asset-level climate risk assessment (vs aggregate risk scores) is key to avoid large understimation of losses.

Related work: carbon risk pricing

Impact of climate policies on prices/premia (stocks/bonds/loans)

- Equity (Monasterolo and de Angelis, 2020 EE, 2023; Pastor ea. 2022 JFE; Bolton and Kacperczyk 2021 JFE; Avramov ea. 2021 JFE, Zerbib 2022, etc.)
- Bond Alessi ea. 2021 JFS; Zerbib 2019 JBF; Ehlers ea. 2022 JBF)
- Credit, derivatives Capasso ea. 2020 JCF; Nguyen ea. 2022 RFS, Ilhan ea. 2021 RFS
- Results: mixed sign of impacts, magnitude only up 20-30 bp

Carbon risk could be only partially priced by markets

- "Lack of consensus among institutional investors around climate change" (Bolton and Kacperczyk 2021 JFE)
- Stroebel and Wurgler (2021 JFE): consistent view among financial economists and professionals that climate risks are underestimated and policy risk is the dominant one in the near term
- Uncertainty about mitigation scenarios (Barnett ea. 2022 RFS).

Related work: corporate finance

Related works in financial valuation

- Similar to financial valuation models, we relate the adjustment in PD to future cash flows:
    - Established literature on the relation between the firms' future economic performance and the value of firms' securities (Brennan and Schwartz 1984, Campbell and Shiller 1988)
    - Recently also applied to sustainable and responsible investing (Crifo et al. 2015, Renneboog et al. 2008, etc.)
    - Valuation varies depending on discount rate (Krueger et al. 2015) and on the trajectory of future cash flows, e.g. oil prices scenarios (Haushalter et al. 2002, Jin and Jorion 2006).

Related work: climate change and credit risk

Relation to structural models of credit risk

- Similar to structural models of credit risk, default is modelled as the result of a process internal to the firm (Merton, 1974):
  - Agliardi and Agliardi 2021: structural model (Merton + jumps) for bond risk with jump distribution linked to green/non-green bond
  - Le Guenedal and Tankov 2022: structural model of defaultable bonds, probability of a scenario inferred from carbon price shocks
- Differences:
  - climate scenario-contingent valuation
  - simplified mathematical treatment, more detailed economic structure for financial valuation: discounted cash flows
  - focus on dynamic evolution of firms' energy tech
  - internalization of investors' expectations in credit risk adjustments

The model: information structure

- Known: set of possible climate policy scenarios (NGFS)
- Known: conditioned to a scenario, trajectory of output for each energy tech.; probability distribution of profitability shocks
- Unknown: probability of occurrence of each scenario
  - Expectations and beliefs about which scenario will occur may change upon arrival of new info (policy, tech, market news)
- Frictions:
  1. Markets' changes of expectations on scenarios not fully anticipated
  2. Once a change of expectations occurs, firms face some net costs in selling off excess capital stock (carbon stranded assets)
  3. Insurance market to cover ex-ante for these losses is incomplete

The model: production and capital stock

- Economy with discrete time indexed by $t \in \mathbb{N}$
- Economic activities classified into Climate Policy Relevant Sectors (CPRS, Battiston ea. 2017; 2022) indexed by $s = 1, \cdots, S$
- Firms maximise profits, with Cobb-Douglas production function $g_s(\tilde{K}, \tilde{L}) = \mu_s \tilde{K}^{\alpha_s} \tilde{L}^{1-\alpha_s}$, with $\tilde{K}$, $\tilde{L}$ real capital and labour
- Production function in sector s is linear in the capital level that maximises firm's profits[1], with productivity of capital $\lambda_s := 1/\alpha_s$:

$$f_s(K) = \lambda_s K$$

- Capital in sector s depreciates at rate $\delta_s \in [0, 1]$.

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[1] Under assumption that labor supply and wages are fixed.

The model: climate policy uncertainty

- Set of scenarios: Business-as-usual scenario B and a set of climate policy scenarios $\mathcal{P} = \{P_1, \cdots, P_n\}$.
- Each scenario P characterized by target temperature and by trajectories of economic output across sectors s and over time t:

$$\{X^P_{s,t}\}_{s,t} \quad \text{with } s = 1, \cdots S, \quad t = 0, \cdots, t_{\max}$$

- Possible switching of market expectations from B to P
- 2 sources of uncertainty:
  - Knightian uncertainty about the scenario
  - Probabilistic uncertainty about econ and financial dynamics in a given scenario (captured by distribution of the profit rate): driver of credit risk within a scenario.

Transition risk exposure: Climate Policy Relevant Sectors

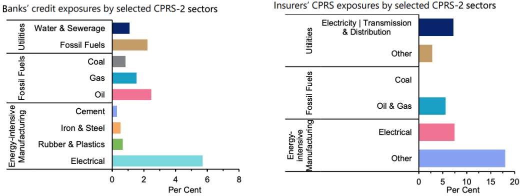
Climate Policy Relevant Sectors (CPRS)

- Sectors *s* are characterised by different levels of transition risk and classified into CPRS (NACE 4-digit) (Battiston ea. 2017)
- Forward-looking transition risk classification of individual activities and assets, widely used in the literature and finance practice.
- CPRS consider:
  - Energy tech composition of revenues
  - Business model and input substitutability (fossil fuel)
  - Contribution to GHG emissions (Scope 1,2,3)
  - Relevance for climate policy implementation (costs sensitivity, e.g. to EU carbon leakage directive 2003/87/EC)

Examples of CPRS application by financial supervisors

Chart S1.2 CPRS-2 allows for more granular sectoral analysis of transition risk for banks...

Chart S1.3 ... and insurers



Source: Banks' submissions, MAS estimates

Source: Insurers' submissions, MAS estimates

Figure: Application of CPRS at the Monetary Authority of Singapore (MAS), Financial Stability Review. Source: MAS, 2023

- EIOPA Financial Stability Report Dec. 2018; Dec. 2019
- ECB Financial Stability Report, May 2019, 2020, etc
- EC JRC study of EU Taxonomy financial impact 2021
- EBA Risk assessment of the EU banking system, Dec. 2020
- National Bank of Austria Financial Stability Report 2020
- MAS Financial Stability Review 2023

Real dynamics of the firm in the B scenario

- Firm characterized by its market share m in each s and tech $(m_s)_{s \in S}$
- Capital stock needed to fulfill production trajectory under B is determined by market share and production function:

$$K^B_{s,t} := \frac{m_s}{\lambda_s} X^B_{s,t}$$

- In turn, this determines the required investment trajectory[2]:

$$I^B_{s,t+1} = K^B_{s,t+1} - (1 - \delta_s) K^B_{s,t}, \quad I^B_{t+1} = \sum_s I^B_{s,t+1}$$

- Finally, profit depends on output with random shocks:

$$\Pi^B_t := \sum_s u^B_{s,t} m_s X^B_{s,t}$$

where $u^B_{s,t}$ is random profit rate.

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[2] We assume that the capital accumulation trajectory induces a non-negative investment pattern in B.

Financial dynamics of the firm in the B scenario

- Financial structure of the firm constrained by the need to finance required investment in the scenario
- Initial capital stock of the firm financed by equity and debt:

$$K_0^B := I_0^B = E_0^B + D_0^B$$

- New investments are financed by new debt and retained earnings
- Given dividend factor d and interest rate r (determined at t = 0), the debt dynamics is[3]:

$$D_t^B := (1+r)D_{t-1}^B + (I_t^B - (1-d)\Pi_t^B) \quad (1)$$

- Expanding Eq.(1), debt at maturity T is:

$$D_T^B = (1+r)^T D_0^B + \sum_{t=1}^{T-1}(1+r)^{T-t} I_t^B - \sum_{t=1}^{T}(1+r)^{T-t}(1-d)\Pi_t^B \quad (2)$$

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[3] We assume initial debt can be extended through a credit line, consistently with empirical evidence on the structure of corporate lending deals.

Changes in expectations (B to P) and stranded assets

- At $t = 0$ markets' expectations switch from B to P
- It takes time delay τ for firms to reduce their fixed capital trajectory when expectations change leading to lower demand for fossil fuels
- Stranding coefficient γ^P: ratio future value of investments in P vs B

$$\gamma^P := \frac{\bar{I}^P_T}{\bar{I}^B_T} = \frac{\sum_{t=0}^{T}(1+r)^T I^P_t}{\sum_{t=0}^{T}(1+r)^{T-t} I^B_t}\,. \tag{3}$$

- Stranding: resulting capital stock $K^P_{s,t}$ differs from efficient trajectory $K^{*P}_{s,t}$ (if the firm anticipated P and adjusted immediately)
- Stranding depends on: adjustment time τ, depreciation rate δ, difference btw production levels in B and P. In the simplest case[4]:

$$K^P_{s,t} := \begin{cases} K^B_{s,t} & \text{if } t \le \tau \\ \max\{K^{*P}_{s,t}\;,\;K^P_{s,\tau}\cdot(1-\delta_s)^{t-\tau}\} & \text{if } t > \tau\,. \end{cases}$$

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[4] The formula is valid in the case illustrated in the plot. More general case treated in the paper.

Changes in expectations (B to P) and stranded assets

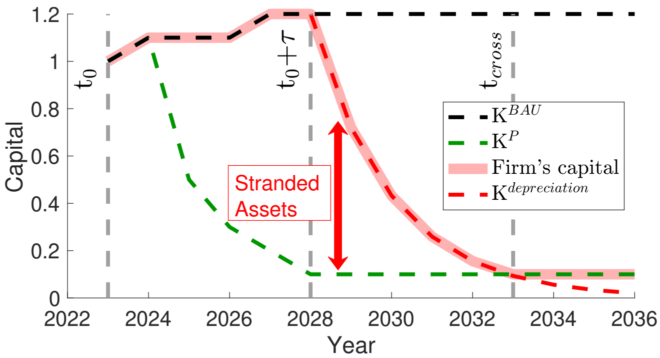

Figure: Capital trajectories in B (black), P (green), stranding (pink). Two frictions (capital lock in in infrastructures, fossil fuel needs) prevent the firm to anticipate stranding (i.e. follow green). Relative stranded assets at t: $\frac{K_t^P - K_t^B}{K_t^B}$

Bond valuation adjustment

- Value $\mathcal{B}_0^C$ of a zero-coupon bond with face value 1 and maturity T in scenario $C \in \mathcal{C}$ is given by

$$\mathcal{B}_0^C = (1 + r_0^C)^{-T}\left[(1 - \mathrm{PD}^C) + \mathrm{PD}^C R^C\right], \tag{4}$$

  where PD^C is the default probability, R^C is the recovery ratio in C under the (risk-neutral) probability $\mathbb{Q}$.

- Valuation adjustment $\Delta\mathcal{B}_0^P$ conditional to changes in markets' expectations (B to P) defined as relative change in valuation[5]:

$$\Delta\mathcal{B}_0^P = \frac{\mathcal{B}_0^P - \mathcal{B}_0^B}{\mathcal{B}_0^B} = \frac{-(1 + r_0^P)^{-T} PD^P LGD^P + (1 + r_0^B)^{-T} PD^B LGD^B}{(1 + r_0^P)^{-T}(1 - PD^B LGD^B)} \tag{5}$$

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[5] Dependency on financial parameters (E_0, r, d) omitted to simplify notations.

Default probability and credit risk

Proposition. Default probability and key parameters

1. The risk-neutral default probability in scenario $C = \{B, P\}$ is function $PD^C(E_0, r, d, \mathbf{X}^C, \mathbf{X}^B, \lambda, \delta, \gamma)$ of: initial equity E_0, interest rate r, dividend rate d, output trajectories $\mathbf{X}^C$, $\mathbf{X}^B$ in scenarios B, P, productivity λ, depreciation rate δ and delay parameter τ.
    - PD^C decreases with E_0 and increases with d
    - PD^C increases with r for λ_s large enough
2. If $X^P_{t,s} \leq X^B_{t,s} \forall t, s$ (strictly $\exists t, s$) and stranding coefficient γ close enough to 1, the default threshold in P is higher than in B:

$$\theta^P > \theta^B.$$

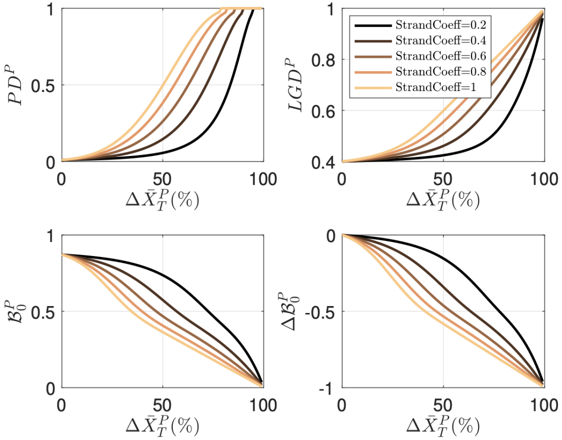
Implications for credit risk

Upon changes in markets' expectations from B to P, PD increases

$$PD^P(E_0, r, d, \mathbf{X}^P, \mathbf{X}^B, \lambda, \delta, \gamma) > PD^B(E_0, r, d, \mathbf{X}^B, \lambda, \delta).$$

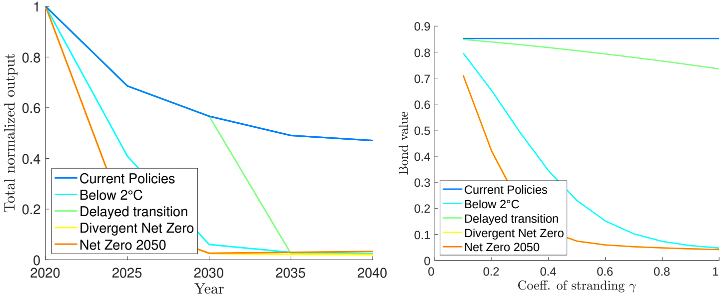
if production is lower and distrib. of profitability rates v^P,v^B are close enough.

Sensitivity analysis



Dependence of key quantities on change in the cumulative compounded output $\Delta\bar{X}_T^P = -\frac{\bar{X}_T^P - \bar{X}_T^B}{\bar{X}_T^B}$ (loss in cumulative output: B to P) Top left panel: yearly PD. Top right: LGD. Bottom left: bond value $\mathcal{B}_0^P$. Bottom right: bond valuation adjustment $\Delta\mathcal{B}_0^{BP}$.

Output and bond value across scenarios and stranding



For single tech firm (electricity/coal revenues):

- Left: output in Net Zero 2050 always smaller than in Below 2C (the latter being less stringent on emission reduction)
- Right: bond value in Net Zero 2050 is also lower than in Below 2C. As expected, stronger effects for higher value of stranding.

Dynamic energy technology and output evolution

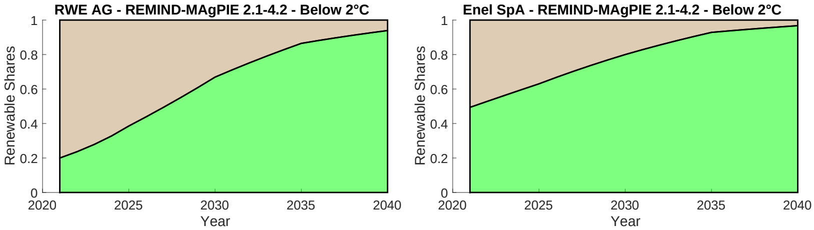


Figure: Evolution of output share from renewable (green) and non-renewable technologies (brown), for two example companies, RWE AG (left) and Enel SpA (right), under scenario Below 2C, REMIND-MagPIE 2.1-4.2.

Valuation adjustment of individual bonds

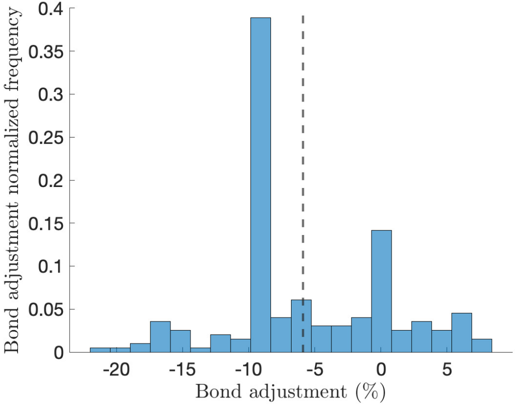


Figure: Histogram of bonds' valuation adjustment across firms conditional to change in markets' expectations from Current Policy to Net Zero 2050, REMIND-MAgPIE 3.0-4-4. The vertical black dashed line represents the average adjustment across firms which also corresponds to the average adjustment for a portfolio allocation with uniformly distributed weights (i.e., a "one-over-N" investment allocation).

Example portfolio (w/technology evolution)

- Investment universe: 198 global listed companies in utility sector with info on power technology capacity in 2020
- We build 5 portfolios based on firms' greeness: $-1 \leq \text{greenness} = C_{\text{Ren}} - C_{\text{Foss}} \leq 1$:
    - **Top10Green**: "one-over-n" allocation into top 10% of firms by greenness
    - **Top50Green**: "one-over-n" allocation into top 50% of firms by greenness
    - **All**: "one-over-n" allocation into all firms
    - **Bottom50Green**: "one-over-n" allocation into bottom 50% of firms by greenness
    - **Bottom10Green**: "one-over-n" allocation into bottom 10% of firms by greenness.

Valuation adjustment of bond portfolios across scenarios

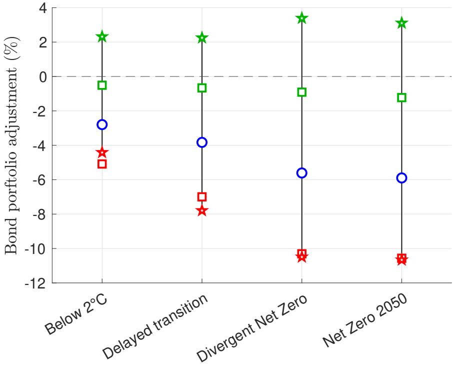


Figure: Valuation adjustments of bond portfolios across scenarios. Market expectations: change from Current Policy to each scenario, REMIND-MAgPIE. Portfolio allocations: Top10Green (green star); Top50Green (green square); All (blue circle); Bottom50Green (red square); Bottom10Green (red star).

Conclusion

- CLIMACRED model for climate scenario-contingent valuation
- Closed-form expression for valuation adjustment under changes in markets' expectations
- *Potential* carbon risk is large: up to 80% loss in value for firms active only in fossil fuel vs. lower for firms with diversified tech
- Adjustment driven by (i) sector output trajectory, (ii) firm-level tech. mix, (iii) firm-level stranding
- Empirical applications to climate stress-testing (e.g. MAS), NGFS short term scenarios project, DG REFORM ESG UPTAKE project.

APPENDIX

CPRS mapping

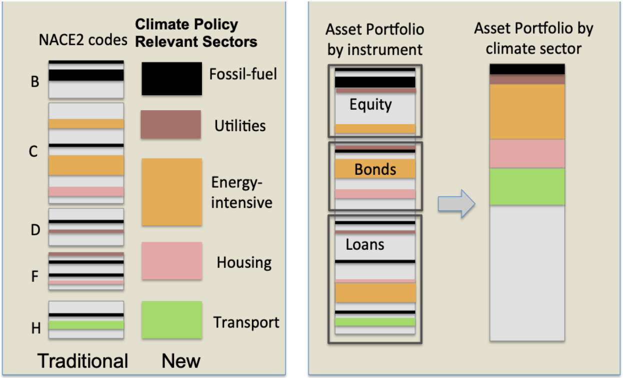


Figure: Source: Battiston ea. 2017

Probability of default in policy scenario B

Proposition on default probability in B

The default condition in scenario B, is such that the average shock on profitability v^B *is* $\leq$ *threshold* θ*, function of: initial equity* E_0*, interest rate* r*, dividend rate* d *and output trajectory* $\{X^B_{s,t}\}_{s,t}$*, as:*

$$v^B \leq \theta(E_0, r, d, \{X^B_{s,t}\}_{s,t}) = \frac{\overline{I}^B_T - A^B_T - \overline{E}_T}{(1-d)\overline{X}^B_T} .$$

- *where:*
  - θ *is decreasing in* E_0 *and* d*, ceteris paribus,*
  - $\overline{E}_T := (1+r)^T E_0$ *future value of initial equity at growth rate* r*,*
  - $\overline{X}^B_T := \sum_{t=1}^{T}(1+r)^{T-t}\sum_{s=1}^{S} m_s X^B_{s,t}$ *future value of output,*
  - $\overline{I}^B_T := \sum_{t=0}^{T-1}(1+r)^{T-t} I^B_t$ *future value of investment,*
  - $v^B := \dfrac{\sum_{t=1}^{T}(1+r)^{T-t}\sum_{s=1}^{S} u^{B,s}_t m_s X^B_{s,t}}{\sum_{t=1}^{T}(1+r)^{T-t}\sum_{s=1}^{S} m_s X^B_{s,t}}$ *random variable denoting the average profit rate across sectors and time periods.*

Probability of default in the policy scenario P

Proposition on default probability in P

The default condition in scenario P, is s.t. the average shock on profitability v^P is $\leq$ threshold θ, function of: initial equity E_0, interest rate r, dividend rate d, stranding coefficient γ, and output trajectory $\{X^P_{s,t}\}_{s,t}$, as:

$$v^P \leq \theta(E_0, r, d, \gamma, \{X^P_{s,t}\}_{s,t}) = \frac{\gamma^P \overline{I}^B_T - A^P_T - \overline{E}_T}{(1-d)\overline{X}^P_T} \,.$$

- *where:*
  - θ *is decreasing in* E_0 *and* d*, and increasing in* γ*, ceteris paribus,*
  - $\overline{E}_T := (1+r)^T E_0$ *future value of initial equity at growth rate* r*,*
  - $\overline{X}^P_T := \sum_{t=1}^{T} (1+r)^{T-t} \sum_{s=1}^{S} m_s X^P_{s,t}$ *future value of output,*
  - $\overline{I}^P_T := \sum_{t=0}^{T-1} (1+r)^{T-t} I^P_t$ *future value of investment,*
  - $\gamma = \frac{\overline{I}^P_T}{\overline{I}^B_T}$ *non decreasing in* τ*,*
  - v^P*: defined analogously to* v^B

Loss Given Default (LGD)

- If no default: zero-coupon yields a payment corresponding to the principal of debt plus interests. If default: the firm can pay the value of its assets (lower than face value of debt)
- In any scenario $C \in \mathcal{C} = \{B, P_1, \cdots, P_n\}$, *endogenous* recovery rate R^C is the expected value of bond repayment conditional to default
- Loss Given Default (LGD) in C is $LGD^C = 1 - R^C$
- We have:

$$LGD^C = 1 - R^C = 1 - \mathbb{E}_{\mathbb{Q}}\left[\frac{\kappa A_T^C}{D_T^C} \,\middle|\, A_T^C < D_T^C \right],$$

where κ: exogenous coefficient capturing bankruptcy costs.

Evolution of output by technology: RWE and ENEL examples

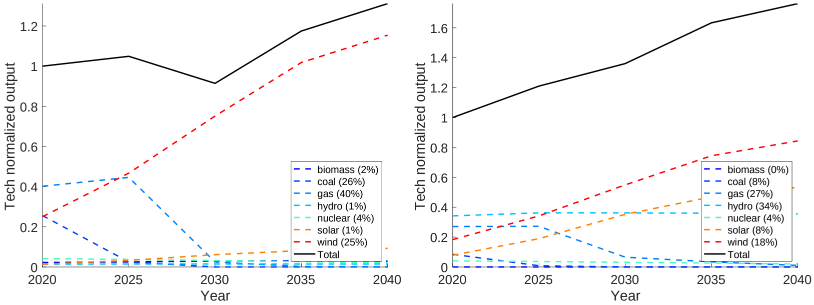


Figure: Evolution of output by technology for RWE AG (left) and Enel SpA (right) computed with scenarios from REMIND-MagPIE 3.0-4.4 Net Zero 2050. Dashed lines: output by technology (color code in legend). Black solid line: total output, 2020=1. Legend: % by technology at 2020.

Evolution of output across scenarios

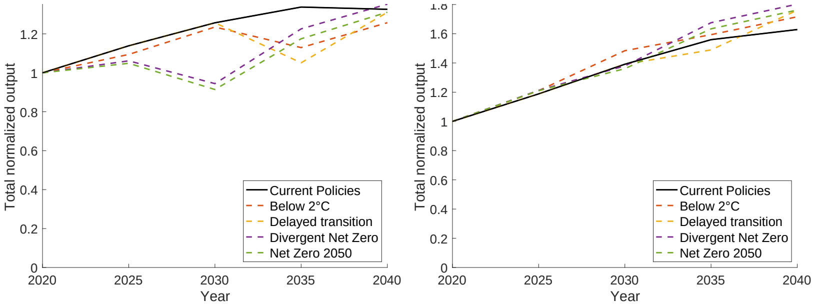


Figure: Comparison across climate policy scenarios of total firms' size estimated with model REMIND-MagPIE 3.0-4.4 for RWE AG (left) and ENEL SpA (right). The dashed lines represent climate policy scenarios, the black solid line represents the Business as Usual (BAU) scenario. Dashed lines deviate from the black solid line at the moment when the transition occurs. For this reason, the line representing the Delayed transition scenario overlaps with the BAU line until the year 2030.

Evolution of output by technology: RWE and ENEL examples

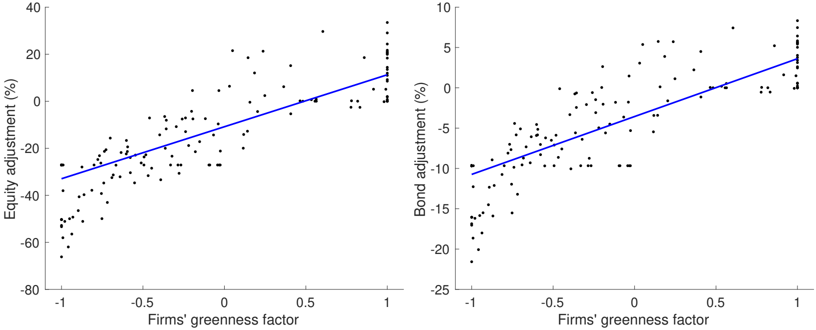


Figure: Comparison of the level of greenness of utility firm with respect to equity (left) and bond (right) adjustments computed with scenarios from REMIND-MagPIE 3.0-4.4 Net Zero 2050. Firms' greenness is defined as the aggregate initial tech share from renewable activities minus the aggregate initial tech share from fossil based activities.