Virtual Seminar on Climate Economics
Federal Reserve Bank of San Francisco

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On the dependence of investor’s probability of default on climate transition scenarios

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Section 1

Background and motivation
Climate change: a new type of financial risk

- Central banks and financial regulators are increasingly concerned about **climate-related financial risks** (Carney 2015, FSB 2020):
  - **physical** risk: emissions concentration affects hazards and losses
  - **transition** risk: change in climate policy, regulation, technology affect firms’ performance based on energy technology

- Financial supervisors worry about the impact of a **disorderly transition** on **financial stability** (NGFS 2019, FED 2020, etc)
  - Late/sudden introduction of climate policies whose impacts cannot be fully anticipated by investors

- Several central banks and financial regulators joined the Network for Greening the Financial System (NGFS):
  - Guidelines on **climate stress test** scenarios (NGFS 2020)
  - In action: some central banks developed climate stress tests (Dutch Central Bank 2019, Banque de France 2020).
Their concerns are grounded in research results:

- Dietz ea (2016): climate value at risk (VaR) of global financial assets is 1.8 percent along a business-as-usual emissions path (USD2.5 trn), much of risk in the tail.

- Battiston ea (2017)’s Climate stress test: investors are exposed to activities (Climate Policy Relevant Sectors-CPRS) that can face losses and become stranded assets in a disorderly transition:
  - 43-45 percent of equity holdings’ portfolios of pension funds and investment funds; banks most exposed to fossil and utility via loans.
  - Risk can be amplified by reverberation in the network of interconnected financial actors, creating conditions for systemic risk.

Why risk? Investors have large exposures to CPRS

- Classification of financial assets’ transition risk is provided by **Climate Policy Relevant Sectors (CPRS)**, (Battiston ea. 2017): Fossil fuel, Utility, Energy intensive, Housing, Transport, Agriculture

- CPRS overcome key limitations of approaches based only on emissions by considering firms’ energy technology mix and policy sensitivity, to operationalize the notion of **stranded assets**

![Diagram showing equity exposure of various banks]
CPRS is applied by several financial supervisors

- **European Commission** JRC study of EU Taxonomy financial impact (EU equity and bonds market, this figure), 2019
- **EIOPA** Financial Stability Report 2019
- **European Central Bank** (2019)’s Climate change and financial stability (Financial Stability Review 2019)
- **EBA** Risk assessment of the EU banking system, Dec. 2020
- **National Bank of Austria**, Financial Stability Report 2020

Source: Alessi et al. (2019) financial impact assessment of the EU Taxonomy
Large direct/indirect exposures may trigger systemic risk

Value at Risk (5% significance) on equity holdings of 20 most affected EU banks under scenario of green (brown) investment strategy. Dark/light colors: first/second round losses. Source: Battiston *et al.* (2017). A climate stress test of the financial system. *Nature Climate Change*

1st round (top): brown bank incurs more losses.
Adding 2nd round (bottom) polarizes distribution of losses.
Knowledge gaps for supervisory activities

- Better understanding is needed of how climate transition risk affects financial assets and investors’ financial stability.
- In particular, we need to understand how sensitive are investor’s risk metrics (Probability of default (PD) and Expected Shortfall (ES)) to the probability of occurrence of disorderly scenarios (the risky ones).
- This is crucial for climate financial risk supervision and risk management strategies (incl. relevant scenarios for climate stress testing). But it is still missing in the literature.
Section 2

Contribution of the paper
Climate change brings about a new type of financial risk that standard approaches to risk management are not adequate to handle.

With analytical and computational work, we study:

- **Valuation adjustment of bonds** (corp.) based on available knowledge on climate transition scenarios (carbon pricing).
- How PD of bonds depends on the interplay between energy technology profile of firm activities (high/low-carbon), climate transition scenarios, considering deep uncertainty on probabilities.
- Sensitivity of investor PD and ES to climate-adjusted bond PD and to the probability of occurrence of disorderly scenarios (including NGFS ones).

We consider how PD varies across all spaces of portfolio configurations (high/low-carbon assets) that include also equilibrium portfolio.
This paper is about climate transition risk

- Many economic papers consider climate risk only in terms of GHG emissions and/or disasters (i.e. backward-looking data on temperature, emissions, losses)
- However, **climate transition risk** is relevant for finance even before climate physical risk: time horizon (5-10y)
  - Relevant variables: energy technology profile of activity, policy design
- Assessing climate transition risk is more challenging:
  - **Forward-looking**: historical info. is not a good proxy of future risks
  - Many firms issuing green bonds have multiple activities (low/high-carbon)
- Thus, we need to work with transition scenarios (e.g. those produced by Integrated Assessment Models (IAMs))
Economic intuition

- If markets price efficiently climate risk (high carbon firms are more risky) and anticipate policy impact, transition risk not financially relevant. However, no clear signals.

- **Friction:** deep uncertainty on climate transition scenarios, their probability of occurrence and their impact, means that agents are not able/willing to internalise information on transition risk.

- Issuers can vary share of investments in low/high carbon activities, investors can vary portfolio composition across issuers. However, forward-looking risk make full hedging not possible.
Main results

- The PD and ES of a leveraged investor increase non-linearly with the impact of the climate policy shock on revenues of corp. bond issuer (in low/high-carbon activities).
- The PD of a leveraged investor is sensitive to small changes in adjusted bond PD, to the probability of occurrence of disorderly climate transition scenarios.
- Thus, assumptions on the sets of climate transition scenarios and their probability of occurrence play a main role for investors’ risk management.
Take home messages for financial supervisors involved in climate financial risk management (NGFS, ECB’s Climate Change center, NY FED’s Supervision Climate Committee):

1. Investors’ PD can be highly sensitive to choice and probability of occurrence of climate transition scenarios.
2. Thus, in order to limit the underestimation of losses due to climate transition risk, **climate stress test** exercises should allow for wide enough sets of scenarios.
3. Our model provides an **operative framework** to assess the dependence of investors’ PD on the choice of climate scenarios, applicable with several types of climate economic and macroeconomic models.
Section 3

The model
### Scenarios

#### Definitions

1. **Set of Climate Policy Scenarios** $P$ corresponding to GHG emission reduction targets (e.g. 2degC) across regions ($B = \text{Base, no policy}$):
   
   $$\text{ClimPolScen} = \{B, P_1, ..., P_l, ..., P_{n_{\text{Scen}}}\}$$

2. **Set of economic output trajectories for each sector $S$, country $C$, scenario $P$, estimated with given climate economic model $M$**:
   
   $$\text{EconScen} = \{Y_{1,1,1,1}, ..., Y_{C,S,P,M},...\}$$

3. **Set of forward-looking (disorderly) Transition Scenarios**:
   
   $$\text{TranScen} = \{BP_1, ..., BP, ..., BP_{n_{\text{Scen}}}\}$$

4. **Set of Climate Policy Shocks**: differences on economic output for $S$, $C$, from $B$ to $P$, estimated with model $M$

   $$\text{PolShock} = \{..., \frac{Y_{C,S,P,M} - Y_{C,S,B,M}}{Y_{C,S,B,M}}, ...\}$$
### Example of orderly and disorderly scenarios

#### Emissions

**Representative Scenarios**

- **Gt emissions / year**
  - **2020**
  - **2030**
  - **2040**
  - **2050**
  - **2060**
  - **2070**

#### Mapping of the representative scenarios to the Framework

- **High**
  - **Disorderly**
  - **Too little, too late**
- **Low**
  - **Orderly**
  - **Hot house world**

**Source:** IIASA NGFS Climate Scenarios Database, using marker models.

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**Dependence of investor’s risk on climate transition scenarios**
Impact of a disorderly transition on firm's revenues

- Decompose net shock on revenues of issuer $j$ (with $u_j, s$: relative shock on $S$; $w_j, s$: share of $j$’s revenues from $S$):

$$u_j(BP) = \frac{\text{rev}_j(P) - \text{rev}_j(B)}{\text{rev}_j(B)} = \sum_s \left( \frac{\text{rev}_{j,s}(P) - \text{rev}_{j,s}(B)}{\text{rev}_{j,s}(B)} \cdot \frac{\text{rev}_{j,s}(B)}{\text{rev}_j(B)} \right)$$

$$= \sum_s \left( u_{j,s}(BP) \cdot w_{j,s}(B) \right), \quad (1)$$

- Focus on CPRS: Primary Energy Fossil ($PrFos$), Electricity Fossil ($ElFos$), Renewable ($ElRen$):

$$u_j(BP) = u_{j,PrFos}(BP) \cdot w_{j,PrFos}(B) +$$

$$u_{j,ElFos}(BP) \cdot w_{j,ElFos}(B) + u_{j,ElRen}(BP) \cdot w_{j,ElRen}(B). \quad (2)$$

- Impact of Transition Scenario $BP$ on revenues $u_j$, result in shock $\xi_j(BP)$ on $j$’s assets ($\chi_j^0$ denotes elasticity):

$$\xi_j(BP) = \chi_j^0 \cdot u_j(BP) \quad (3)$$
Impact of a disorderly transition on firm’s revenues

Remarks

- Firm is considered as a portfolio of (low/high carbon) activities
- In a disorderly transition, high-carbon (low-carbon) activities will incur losses (gains) from carbon-stranded assets
- Shock on $j$’s revenues, $u_{j,S}(BP)$, can be approximated as a shock on output of the corresponding economic activities $S$ (e.g. ELFos) in the economy provided by climate economic models (e.g. IAM)
- Which transition scenarios will occur is uncertain and endogenous because it depends on governments’ climate policies and investors’ expectations and reactions (climate sentiments, Dunz et al., 2020)
Securities: corporate bonds

Basic facts for zero-coupon defaultable bonds

- Risky (defaultable) bond of issuer \( j \), issued at \( t=0 \) with maturity \( T \)
- Bond value at \( T \), with \( R \) bond Recovery Rate (i.e. % of notional recovered upon default); LGD Loss-Given-Default (i.e. % loss)

\[
v_j(T) = \begin{cases} R_j = (1 - \text{LGD}_j) & \text{if } j \text{ defaults (with prob. } q_j) \\ 1 & \text{else (with prob. } 1 - q_j) \end{cases}
\]

- Expected value of bond’s payoff is given by:

\[
\mathbb{E}[v_j] = (1 - q_j) + q_j R_j = 1 - q_j (1 - R_j) = 1 - q_j \text{LGD}_j
\]

- Bond price \( v_j^* \): bond discounted expected value, with \( y_f \) risk-free rate. Price defines implicitly bond yield \( y_j \) (risk neutral measure) as:

\[
v_j^* = e^{-y_f T} \mathbb{E}[v_j] = e^{-y_f T} (1 - q_j \text{LGD}_j) = e^{-y_j T}
\]

- Bond spread defined as: \( s_j = y_j - y_f \), with \( e^{-s_j T} = 1 - q_j \text{LGD}_j \)

- Useful fact: for small \( s_j \), spread = expected loss

\[
s_j \approx \frac{1}{T} q_j (1 - R_j) = \frac{1}{T} q_j \text{LGD}_j
\]
Corporate default

**Shocks and default condition**

- Issuer $j$ balance sheet: $A_j(t_0), A_j(T)$ asset, $t_0 = 0$ issue time, $T$ maturity; $L_j(T)$ liability.

- Default condition: structural model, discrete time (Merton 1974)
  
  $$A_j(T) = A_j(t_0)(1 + \eta_j(T)) < L_j(T)$$

  - $\eta_j(T) \in \mathbb{R}$: idiosyncratic shock (e.g. firm $j$ productivity),
  - $\phi(\eta_1, ..., \eta_j, \eta_n)$ joint probability distribution of issuers (defaults possibly correlated)

- We add climate policy shock $\xi_j(BP)$ on $j$’s assets (“jump” up/down)

- New default condition reads:
  
  $$A_j(T) = A_j(0)(1 + \eta_j(T) + \xi_j(BP)) < L_j(T)$$

  $$\iff \eta_j(T) \leq \theta_j(BP) = L_j(T)/A_j(0) - 1 - \xi_j(T, BP)$$

- $\theta_j(BP)$ default threshold under scenario $BP$
- $\xi_j(BP)$ positive/negative: $\xi_j(BP) > -1$, correlated across $j$
Section 4

Results
Definition and Proposition

- Climate Spread $\Delta s_j$ is change in spread $s_j$, conditional to transition scenario $BP$:
  \[
  \Delta s_j = s_j(q_j(P)) - s_j(q_j(B)).
  \]

- Conditional to transition scenario:
  1. Climate spread reads:
     \[
     \Delta s_j(BP) = s_j(BP) - s_j(B) = \frac{1}{T} \left( \log(v_j^*(BP)) - \log(v_j^*(B)) \right) - \left( y_f(BP) - y_f(B) \right)
     \]
  2. $\Delta s_j(BP)$ increases (decreases) with magnitude of policy shock on revenues $|u_j(BP)|$, if $u_j(BP) < 0$ ($u_j(BP) > 0$);
  3. For small shock $u_j(BP) << 1$:
     \[
     \Delta s_j(BP) \approx - \frac{1}{T} \chi_j \left( u_j,PrFos \ w_j,PrFos + u_j,ElFos \ w_j,ElFos + u_j,ElRen \ w_j,ElRen \right)
     \]
Investor and Portfolio Value-at-Risk

- Leveraged investor: \( \Lambda = A/E \)
- Investor \( i \)'s portfolio value \( z_i \) and portfolio rate of return \( \pi_i \) at \( T \), with \( W_{ij} \) amount (numeraire) of \( j \)'s bond purchased by \( i \):
  \[
  z_i(T) = \sum_j W_{ij} v_j(T), \quad \pi_i = \frac{z_i(T) - z_i(t_0)}{z_i(t_0)}
  \]

- **Climate VaR** is the Value-at-Risk of the portfolio of investor \( i \), conditional to Transition Scenario \( BP \) with: \( \pi \) portfolio return, \( \psi_P(\pi) \) distribution of returns conditional to the Climate Policy Shock, and \( \alpha \) is the confidence level:
  \[
  \int_{-1}^{\text{ClimateVaR}_\alpha(BP)} \psi_{BP}(\pi) \, d\pi = \alpha \quad (4)
  \]

- **Climate ES** is the average of the losses above the Climate VaR:
  \[
  \text{ES}(BP) = \frac{-1}{\alpha} \int_0^{\alpha} \text{ClimateVaR}_{\alpha'}(BP) \, d\alpha' \quad (5)
  \]
Adjustment in investor’s ES and PD

Propositions
We prove several propositions on how investor’s ES and PD are adjusted conditional to a transition scenario (Appendix). In short:

- ES(BP) increases with adjustment on bond default probability q(BP)
- Adjustment of PD of a leveraged investor can be derived analytically (numerically) in absence (presence) of correlation among bonds
- Under some assumptions of homogeneity, ES and PD decrease with share of climate-aligned revenues (i.e. renewable energy activities)
How losses on bond portfolio depend on $q$ and $\rho$

- Probability distribution (y-axis) of losses (x-axis, in %) on example portfolio of 100 bonds, equally weighted.
- Climate ES (vertical bars) move right both with bond default probability $q$ and with default correlation $\rho$. 
Consider a possible discrepancy between estimated \((q, \rho)\) (magenta) and actual (blue, red).

- Large difference in Climate ES; even larger in PD.
Considering adverse scenario mitigate impact of uncertainty on ES and PD

- Adverse scenario occurs with prob. $p_A$. Effect of discrepancy between estimated $(q, p_A)$(magenta) and actual (red) is smaller if investor consider multiple scenarios, but still large.
Conclusion

- We develop a model to compute:
  - the valuation adjustment of a corporate bond, depending both on climate transition risk scenarios and on companies’ shares of revenues across low/high-carbon activities, and
  - the corresponding adjustments in an investor’s PD and ES

- Implications for climate financial risk management: **climate stress tests** should allow for a wide enough set of scenarios to limit the underestimation of losses

- The model provides an **operative framework** applicable with several types of climate and macroeconomic models

- Ongoing follow-up work: i) model calibration, ii) application to compound pandemic and **climate physical risk**.
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Appendix
A note on transition scenarios

- Climate economic models provide scenarios of emissions concentration to achieve 1.5/2°C world
- NGFS uses process-based IAM with granular representation of energy technologies (fossil, renewables)
- **Challenge**: IAM mitigation scenarios do not account for the role of finance in achieving the same scenarios, nor for financial complexity

This has major implications on the design of **disorderly** scenarios:
- Investments assumed to be available without frictions (no credit constraints)
- Trajectories don’t reflect the impact of mitigation scenarios on financial investment decisions

Thus, considering more adverse scenarios on the IAM’s range is important to avoid underestimate **financial risk associated** (Battiston ea. 2020)
Issuer’s default probability: definition

Definition

- **Default probability** $q_j$ of issuer $j$ under Transition Scenario $BP$, with $\phi_{BP}(\eta_j)$ probability distribution of idiosyncratic shock $\eta_j$, $\eta_{\text{inf}}$ lower bound of distribution support:

$$q_j(BP) = \mathcal{P}(\eta_j < \theta_j(BP)) = \int_{\eta_{\text{inf}}}^{\theta_j(BP)} \phi_{BP}(\eta_j) \, d\eta_j$$

Definition. Default prob. adjustment $\Delta(BP)$

- Intuition. Frequent small productivity shocks across time and firms occur in a similar way with/without climate policy shock. Then, the policy shock shifts the probability distribution of productivity shocks and thus $j$ default probability.
- Idiosyncratic shocks are independent from policy shock
- Result. Default probability adjustment under transition scenario:

$$\Delta q_j(BP) = q_j(P) - q_j(B) = \int_{\theta_j(B)}^{\theta_j(P)} \phi(\eta_j) \, d\eta_j, \text{ with } \theta_j(P) = \theta_j(B) - \xi_j(P)$$
Issuer’s default probability: proposition

**Proposition. Default prob. adjustment $\Delta q_j(BP)$**

- Assuming
  - idiosyncratic shocks are **independent** from policy shock
  - policy shock on asset proportional to shock on revenues via elasticity $\xi_j = \chi^0_j u_j(BP)$
- Then, the **adjustment** in default probability $\Delta q_j(BP)$
  - increases with shock magnitude $|u_j(BP)|$ if $u_j^{BP} < 0$, and decreases vice versa
  - Under approximation of small policy shock, $\Delta q_j(BP)$ can be linearized to be proportional to shock on CPRS revenues:

$$\Delta q_j(BP) \approx -\chi_j \left( u_j,\PrFos(BP) w_j,\PrFos + u_j,\ElFos(BP) w_j,\ElFos + u_j,\ElRen(BP) w_j,\ElRen \right).$$
Definition and Proposition

The adjustment in the value of the issuer’s bond conditional to the Transition Scenario BP, $\Delta v_j^*(BP)$, is defined as the change in the discounted expected value of the bond, resulting from the Transition Scenario $BP$ on issuer $j$’s revenues $u_j(BP)$:

$$\Delta v_j^*(BP) = v_j^*(BP) - v_j^*(B)$$  (6)

The following properties hold:

(i) The expression of the adjustment of the value of the bond $\Delta v_j^*$, conditional to $BP$ reads:

$$\Delta v_j^*(BP) = v_j^*(q_j(BP)) - v_j^*(q_j(B)) = -e^{-y_f T} \Delta q_j(BP) \text{LGD}_j$$  (7)
Proposition

Consider a leveraged investor with an equally weighted portfolio, of zero-coupon bonds, with issuers having independent defaults occurring with the same probability \(q\) and with the loss-given-default LGD. The following properties hold:

(i) The investor’s PD, \(P(m, \Lambda, q)\) can be expressed in terms of the binomial distribution \(B(m^*, m, q)\):

\[
P(m, \Lambda, q) = P(X \geq m^*) = 1 - B(m^*, m, q)
\]  

(ii) The investor’s PD is non decreasing in: a) the investor’s leverage \(\Lambda\); b) the loss-given-default LGD; c) the bond default probability \(q\).
**Proposition**: Example effect of climate-aligned investment

Consider:

- an equally weighted portfolio of zero-coupon bonds with the same PD, $q$, and the same loss-given-default $LGD$
- all issuers $j$ have the same shares of revenues across the three sectors Primary Energy Fossil, Electricity Fossil, Electricity Renewable, $w_j, Pr_{Fos}(B), w_j, El_{Fos}(B), w_j, El_{Ren}(B)$
- transition scenario BP such that $u_j, Pr_{Fos}(BP) < 0$, $u_j, El_{Fos}(BP) < 0$, $u_j, El_{Ren}(BP) > 0$ and the net shock on revenues $u_j(BP) < 0$ for all $j$

Then, 

(i) Then, $ES(BP)$ decreases with the share of revenues $w_j, El_{Ren}(B)$

(ii) Then, $PD(BP)$ decreases with the share of revenues $w_j, El_{Ren}(B)$