Economics of Climate Change and Green Finance

Antoine Mandel[1]

Cours Bachelier

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[1] antoine.mandel@univ-paris1.fr

Summary

- A short introduction to current issues in the economics of climate change through the lens of financial stability.
- Economic and financial impacts of climate change ("physical risks")
- Economic and financial impacts of climate change mitigation ("transition risks")

Outline

Motivation: Climate change and financial stability

Concerns among financial supervisors of impacts of climate change on financial stability:

- BoE Governor McCarney' s speech on "breaking the tragedy of the horizon" (2015) emphasizes that

  Shifts in our climate bring potentially profound implications for insurers, financial stability and the economy.[...] once climate change becomes a defining issue for financial stability, it may already be too late.

- Central Banks and Supervisors Network for Greening the Financial System (NGFS, 2018, 2019) emphasizes that:

  Climate-related risks are a source of financial risk. It is therefore within the mandates of central banks and supervisors to ensure the financial system is resilient to these risks. [...] The NGFS recognises that there is a strong risk that climate related financial risks are not fully reflected in asset valuation.

Motivation: Lessons from the financial crisis

- Concern partly hinges on the precedent of the 2007-2008 financial crisis.
- Massive amplification of losses through financial interdependencies:
  - Direct losses of the financial system on the US subprime mortgage market amount to 500 billion USD (Greenlaw et al. 2008)
  - Triggered losses one order of magnitude greater within the financial system (Mishkin et al. 2011)
  - And almost two orders of magnitude greater for the global economy (Luttrell et al. 2013)
- Additional requirement: account for amplification of climate-related shocks through financial interlinkages (Battiston et al. 2012, Elliott et al. 2014, Acemoglu et al. 2015).

Notions of risk

- In (mathematical) finance, risk is mainly understood as the variability of returns as measured by variance, volatility, risk-measures...
- The assessment and the management of risk is somehow "consequentialist": rather than on its drivers, one focus on its materialisation in market prices.
- Furthermore, it is generally assumed that all relevant information about risk is reflected in asset-prices.
- The broader (disaster) risk literature adopts a more holistic perspective on risk:

$$\text{RISK} = \text{EXPOSURE} \times \text{HAZARD} \times \text{VULNERABILITY}$$

- whereby:
  - Exposure/Exposition: assets that are potentially affected and their characteristics (e.g. buildings in flood plain)
  - Hazard/Alea: Nature and distribution of potential impact/shocks (e.g. distribution of potential flood level)
  - Vulnerability: Scale/Value of damages given hazard (e.g. depth damage function) .

Climate related risks

- Physical Risk
  - Exposure: assets (directly or indirectly) exposed to climate-related natural hazards.
  - Hazard: changes in the distribution of natural hazards induced by climate change.
  - Vulnerability: Impact of natural hazards on the performance of economic actors and/or the value of financial assets
- Transition Risk
  - Exposure: assets in sectors (directly or indirectly) impacted by climate policy.
  - Hazard: Timing and Intensity of climate policy
  - Vulnerability: Impact of climate policy on the performance of economic actors and/or the value of financial assets.

Risk in climate economics

- Risk, in the sense of variability, is mostly absent from climate economic models, which focus on the trade-off between mitigation costs and expected future damages.
- e.g. DICE model (Nordhaus 1992...) :

$$
\begin{cases}
\max_{(C_t,\mu_t)_{t=1,\cdots,T}} & W_t = \sum_{t=1}^{T}(1+\rho)^{-t} L_t \dfrac{[C_t/L_t]^{1-\alpha}}{1-\alpha} \\
s.t & \\
 & Q_t = I_t + C_t \\
 & K_t = I_t + (1-\delta)K_{t-1} \\
 & Q_t = \dfrac{\Omega_t}{1+\Omega_t}(1-\theta\mu_t^{\tau})A_t K_t^{\gamma} L_t^{1-\gamma} \\
 & \Omega_t = \psi_1 T_t + \psi_2 T_t^2 \qquad \text{(“judgmental" calibration)} \\
 & E(t) = \sigma(t)(1-\mu(t))A_t K_t^{\gamma} L_t^{1-\gamma} \\
 & T_t = f((E_\nu)_{\nu\leq t}) \qquad \text{(climate module)}
\end{cases}
$$

where W_t; social welfare, L_t : population, C_t : consumption, I_t : investment, Q_t : production, K_t : capital, μ_t : mitigation/abatment effort, Ω_t : climate impact, T_t : temperature, $\sigma(t)$: carbon intensity, E_t : emissions.

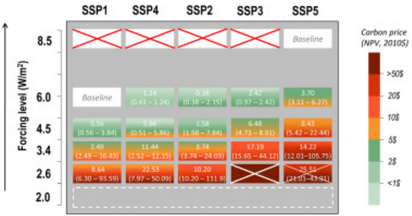
Risk in climate economics

Absence of risk-perspective in climate economic models harshly criticised (Pyndick 2013)

“A plethora of integrated assessment models (IAMs) have been constructed and used to estimate the social cost of carbon (SCC) and evaluate alternative abatement policies. These models have crucial flaws that make them close to useless as tools for policy analysis: certain inputs (e.g. the discount rate) are arbitrary, but have huge effects on the SCC estimates the models produce; the models’ descriptions of the impact of climate change are completely ad hoc, with no theoretical or empirical foundation; and **the models can tell us nothing about the most important driver of the SCC, the possibility of a catastrophic climate outcome."**

Risk and uncertainty in the IPCC framework.

- Account for uncertainties associated to socio-economic developments through scenario-analysis (no probability).
- Scenarios constructed by the combination of a representative concentration pathway (RCP) and a socio-economic pathway (SSP).



- A standard for interactions between (i) climate/earth system modeling , (ii) assessment of impacts, adaptation and vulnerability, (iii) integrated assessment modeling (understanding the drivers of climate change and the effectiveness of potential mitigation policies).

Outline

Agenda

1. Hazard: changes in the distribution of natural hazards induced by climate change.
2. Exposure: assets (directly or indirectly) exposed to climate-related natural hazards.
3. Vulnerability: Impact of natural hazards on the performance of economic actors and/or the value of financial assets.

- Example of coastal floods: (DIVA model, Hinkel et al. 2014)

Hazard: changes in the distribution of extreme sea-levels

- Existing data on global observations of extreme sea levels: global extreme sea-level analysis: www.gesla.org.
- Projections on mean sea-level rise (for each RCP) use results from climate models (GCMs) to estimate oceanic thermal expansion (steric effect), mass changes from glaciers as well as the Greenland and Antarctic ice sheets (each require specific model).
- Beyond RCPs, three scenarios for ice contribution (accounting for uncertainties on ice dynamics)

Table 3: Sea level projections used as input for the DIVA model. Provided are the median as well as the 5% and 95% quantiles in parenthesis (see methods)

Scenario	Model	Steric [cm]	Land-ice [cm]				Total [cm]
			Glacier	Antarctica	Greenland	Sum	
RCP26	HadGEM2-ES	14	14 (14,15)	7 (2,23)	0 (0, 0)	21 (16,39)	35 (29,52)
	IPSL-CM5A-LR	12	12 (12,12)	7 (2,23)	0 (0, 0)	19 (13,36)	30 (25,47)
	MIROC-ESM-CHEM	19	13 (13,13)	7 (2,23)	0 (0, 0)	20 (14,36)	39 (34,56)
	NorESM1-M	15	11 (11,12)	7 (2,23)	0 (0, 0)	18 (13,35)	34 (28,50)
	ALL	15	13 (12,13)	7 (2,23)	0 (0, 0)	20 (14,36)	35 (29,51)
RCP45	HadGEM2-ES	18	17 (16,19)	8 (2,29)	7 (5, 8)	32 (23,56)	50 (41,75)
	IPSL-CM5A-LR	18	14 (14,15)	8 (2,29)	8 (7, 10)	30 (22,53)	48 (40,71)
	MIROC-ESM-CHEM	25	15 (14,16)	8 (2,29)	9 (7, 11)	32 (24,56)	57 (48,81)
	NorESM1-M	20	13 (13,14)	8 (2,29)	3 (2, 4)	24 (17,49)	44 (37,67)
	ALL	20	15 (14,16)	8 (2,29)	7 (5, 8)	29 (21,53)	50 (42,73)
RCP85	HadGEM2-ES	29	22 (20,26)	10 (2,41)	12 (10, 14)	44 (31,81)	72 (60,110)
	IPSL-CM5A-LR	30	18 (17,20)	10 (2,41)	15 (12, 18)	43 (31,79)	73 (61,109)
	MIROC-ESM-CHEM	38	19 (18,21)	10 (2,41)	19 (15, 23)	49 (36,85)	86 (74,123)
	NorESM1-M	32	16 (16,17)	10 (2,41)	6 (5, 8)	33 (23,66)	64 (55,97)
	ALL	32	19 (18,21)	10 (2,41)	13 (10, 16)	42 (30,78)	74 (62,110)

Hazard: changes in the distribution of extreme sea-levels

- For each RCP, projected distribution of extreme sea-levels obtained by translating historical distribution by mean-sea level.
- Let $f_x(y)$ be the probability density for an event (yearly maximum) of elevation $y \in \mathbb{R}_+$ at location (coastal segment) $x \in X$
- For each rcp and ice scenario, one has a mean sea-level rise $\overline{y}^{(rcp,ice)}$, and the resulting hazard density:

$$f_x^{(rcp,ice)}(x,y) = f_x(y - \overline{y}(rcp,ice)).$$

- Coasts are protected (by dikes), the relevant hazard are these that overtop the dykes (and then everything goes as if the dyke breaks).
- If $h(x)$ is the height of the dyke at location x the law of the (yearly maximum) flood level $L_x^{(rcp,ice,h)}$ at location x is given by

$$P(L_x^{(rcp,ice,h)} \leq l) := \left(\int_0^{h(x)} f_x^{(rcp,ice)}(z)dz\right) \mathbb{1}_{[0,+\infty[}(l) + \int_{h(x)}^{l} f_x^{(rcp,ice)}(z)dz$$

Direct exposure: assets exposed to coastal floods

- 12000 coastal segments considered.
- Area exposed to flooding obtained from digital elevation model, yields $a_x(l)$: area under elevation l at location x
- (Historical) population exposed obtained from population density dataset (GRUMP or LANDSCAN), yields $p_x(l)$: population leaving under elevation l at location x.
- Asset exposed determined by applying subnational GDP per capita rates to the population data and an assets-to-GDP ratio of 5 [2], yields $k_x(l)$: value of (physical) assets under elevation l at location x.

Table 2: Global exposed area and population below 2, 4 and 8 m elevation in the base year (1995) for the different DEMs and population distribution models

Digital elevation model	Population distribution	Exposure below 2m Area [10³km²]	Exposure below 2m Population [millions]	Exposure below 4m Area [10³km²]	Exposure below 4m Population [millions]	Exposure below 8m Area [10³km²]	Exposure below 8m Population [millions]
GLOBE	GRUMP	2,465	323	3,559	564	4,425	757
GLOBE	LANDSCAN	2,465	328	3,559	570	4,425	771
SRTM	GRUMP	1,270	123	2,269	352	3,220	542
SRTM	LANDSCAN	1,270	120	2,269	353	3,220	549

- Future exposure is obtained by applying national population and GDP growth rates of SSPs to the coastal segments, yields scenario-specific population, $p_x^{ssp}(l)$, and assets , $k_x^{ssp}(l)$, exposure.

[2] " which is the equilibrium value found in a standard growth model with a labor elasticity of production of 0.2" (Hinkel et aL. PNAS (2014).

Vulnerability

- Vulnerability of assets measured through logistic depth-damage functions: given inundation level l, a share $v(l)$ of the value of assets is destroyed.
- Overall, given scenarios rcp, ice, ssp and protection level h, the risk on physical assets at location x is given by

$$\underbrace{v(l)}_{\text{vulnerability}} \; \underbrace{k_x^{ssp}(l)}_{\text{exposure}} \; \underbrace{d\,\mathcal{L}_x^{(rcp,ice,h)}(l)}_{\text{hazard}}$$

- Most of the analysis in climate economics focus on expected costs/risk (assuming events occur independently over locations):

$$\int_X \left(\int_L v(l) k_x^{ssp}(l) d\,\mathcal{L}_x^{(rcp,ice,h)}(l) \right)$$

Adaptation

- A key driver of risk is the level of protection h.
- Current levels of protection given by empirical observations.
- Dynamics of h are given by adaptation scenario:
  - No adaptation scenario: constant dyke height.
  - Adaptation scenario: dyke raised with sea-level (same probability that dyke is overtopped but larger flooding levels).
  - Optimal adaptation scenario: dykes raised to optimal level determined by cost-benefit analysis.

Distribution of direct economic impacts from coastal floods, constant protection standards

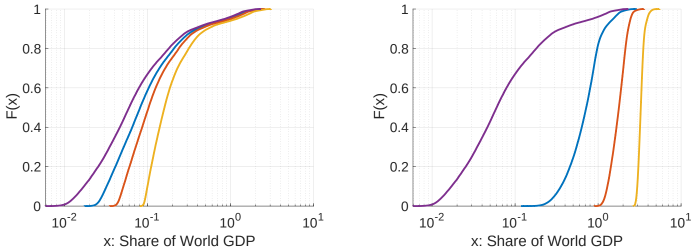


Figure: Simulated cumulative distribution of impacts with (left) and without (right) adaptation for SSP5 and RCP 8.5 at time horizons 2030(blue), 2050 (red) and 2080 (yellow).

- Increase in risk over time in terms of first-order stochastic dominance, i.e. for every risk level r :

$$P(R^{2080} \geq r) \geq P(R^{2050} \geq r) \geq P(R^{2030} \geq r) \geq P(R^{hist} \geq r)$$

Distribution of risks from coastal floods

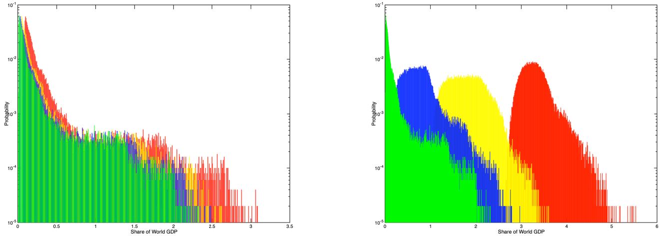


Figure: Histogram of the distribution of impacts with (left) and without (right) adaptation for SSP5 and RCP 8.5 at time horizons 2030(blue), 2050 (yellow) and 2080 (red). Historical distribution in green.

Summary of required models and datasets.

- Global circulation models from CMIP5 (Coupled Model Intercomparison Project).
- Global Extreme Sea Level Analysis dataset.
- Glacier (Randolph Glacier Inventory)
- Antartica Ice model
- Greenland Ice model
- Population density datasets: Global Rural-Urban Mapping Project (GRUMP), LandScan High Resolution global Population Data Set.
- Population and GDP projections from socio-economic scenarios.

Financial stability and indirect exposure

- Concern about financial stability.
- Barrot and Sauvagnat (2016) find econometric evidence of the impact of natural catastrophes on sales and market value of firms and their main customers (impact depend on input specificity).
- Klomp (2014) find econometric evidence that natural catastrophes decrease distance of commercial banks to default.

Shock propagation in financial networks I

- Quantitative models of shock propagation in financial networks (Battiston et al. 2012...).
- $i = 1, \cdots, N$ financial actors characterized by:
    - “external" assets $A_i \in \mathbb{R}_+$.
    - Assets/liabilities towards financial actors $(B_{i,j})_{i,j=1,\cdots N}$ where $B_{i,j}$ (resp.$L_{i,j}$) represents assets (resp. liabilities) of i towards j.
    - Equity of actor i given by $E_i = A_i + \sum_j B_{i,j} - \sum_k L_{i,k}$
- Bankruptcy risk:
    - Actor i faces (common knowledge/expected) idiosyncratic shock ϵ_i, uniformly distributed over $[0, K_i]$ with $K_i > E_i$.
    - If $\epsilon_i > E_i$, actor i goes bankrupt and defaults on its liabilities (zero recovery in the short run).
    - Financial liabilities valued in a risk-neutral manner

$$B_{i,j} = P(\epsilon_j < E_j)L_{j,i} = [E_j/K_j]L_{j,i}$$

where $L_{j,i}$ is nominal value of liabilities.

Shock propagation in financial networks II

- An unexpected (e.g. climate-induced) shock $\mu_j \in \mathbb{R}_+^N$ affects actors j.
- The equity of actor j is reduced to $E_j(1) = E_j - \mu_i$.
- The default probability of actor j increases accordingly and the book value of its liabilities decrease to $B_{i,j}(1) := [E_j(1)/E_j] B_{i,j}$.
- The shocks propagate in the network over time:
  - $E_i(t+1) = \max(0, E_i(t) + \sum_j B_{i,j}(t) - \sum_k L_{k,i})$
  - $B_{i,j}(t+1) = [E_j(t+1)/E_j(t)] B_{i,j}(t)$.
- A number of variants for stopping conditions and/or conditions under which an actor is “contagious" (Battiston et al. 2012, Bardoscia 2015, Barucca et al. 2016)

Impacts of climate shocks on financial assets: data

- As if analysis [3]: impacts of future (relative) damage distribution given current assets and exposures.
- Analysis at the country/institutional sector level: private sector, government sector, insurance, financial (excl. insurance).
- Data on the value of “equity": private sector (physical capital - private debt as % of gdp, from WB/IMF), banking sector (bank capital as % of gdp from IMF).
- Data on exposure: reconstruct domestic and international exposure of the financial sector using data on domestic public/private debt (IMF) and international bilateral exposures through equity, debt and interbank (EU consolidated dataset from IMF and BIS).

[3] Ciscar et al. (2011) "Physical and economic consequences of climate change in Europe." PNAS 108.7 (2011): 2678-2683

Impacts of climate shocks on financial assets: domestic allocation of shocks

$$S_i = \underbrace{\alpha_i S_i}_{I_i \text{ : insured share}} + \underbrace{\min(\phi_i, \max(0, \sigma - \alpha_i) S_i)}_{G_i \text{ : gov share}} + \underbrace{1 - I_i - G_i}_{P_i \text{ : priv share}}$$

where:

- S_i total shock in country i.
- α_i, share of insured damages (Munich Re data)
- σ parameter giving maximal total coverage (insurance role of the state)
- ϕ_i is fiscal space.
- Private sector shock is residual.

Domestic propagation of shocks

Shocks transmitted to the domestic banking sector:

- First-order approximation of impact on liabilities from private sector:
  - value of liabilities proportional to equity E_i
  - impact of a shock P_i proportional to $(E_i - P_i)/E_i$
- First-order approximation of impact on liabilities from government sector:
  - value of liabilities proportional to difference between current debt D_i and maximal sustainable debt $\overline{D}_i$.
  - impact of a shock G_i proportional to $(\overline{D}_i - D_i - G_i)/\overline{D}_i - D_i$
- Share $\gamma I_i/B_i$ of insured damages (where B_i is insurance capital buffer, 99.5 percentile following Solvency II)

Domestic allocation of shocks

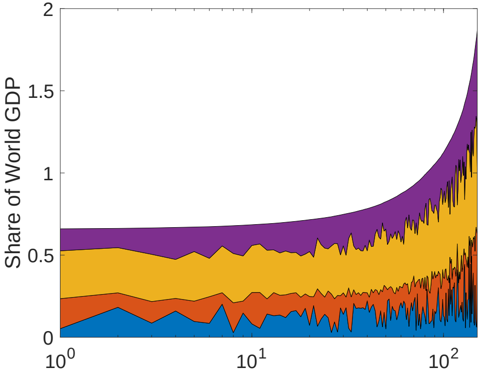


Figure: Components of the domestic impact of floods for a sample of events from the high-impact scenario with adaptation at horizon 2080. The total height of the graph corresponds to the total domestic damages. It is allocated between the insurance sector (blue), the governmental sector (red), private sector (yellow), and domestic impacts on the financial sector (purple).

International propagation of shocks

- Impacts from international holding of equity and debt.
- Propagation within the financial sector according to debtrank algorithm:
  - $F_i(t+1) = F_i(t) + \sum_{\{j \mid F_j(t)>0\}} B_{i,j}(t) - \sum_{j=1}^{N} L_{i,j}$
  - $B_{i,j}(t+1) = \frac{F_j(t)}{F_j(t-1)} B_{i,j}(t)$

where F_i is equity of banking sector in country i, $B_{i,j}$ (resp. $L_{i,j}$) assets (resp. liability) of banking sector of country i relative to banking sector of country j.

Global impacts on financial stability

- Amplification of shocks on country *i* depends on leverage and network centrality of banking sector.
- Total impact depends on magnitude of domestic impact and financial network characteristics

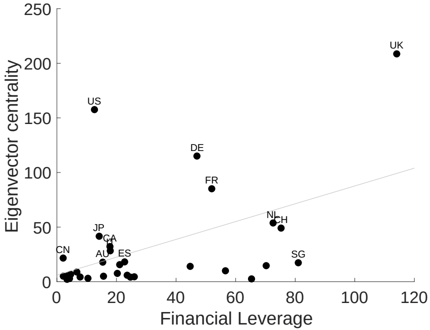


Figure: financial leverage (assets outstanding of domestic financial sector on foreign financial sectors in percentage of gdp) vs eigenvector centrality in bilateral financial exposure network

Single-country var event

historical			adaptation			no adaptation		
Country	global	direct.	Country	global	direct	Country	global	direct
CN	16.5	15.2	CN	21.5	19.7	UK	244.7	27
UK	8.6	2	UK	10.5	2.5	CN	196.2	165.9
DE	5.1	2.8	US	6.5	4.3	JP	130.5	48.9
US	2.8	1.9	DE	5.7	3.1	US	86.3	31.8
FR	2.5	0.8	FR	3	1	DE	61.8	20.5
CA	1.2	0.5	IT	2.8	1.1	FR	61.1	9
IT	1.1	0.4	NO	2.6	0.8	CA	37.8	7.7
DK	1.1	0.3	EG	2.5	1.5	SG	33.2	3.7
NO	0.7	0.3	IN	2.3	2.1	IT	27.8	9.4
IN	0.7	0.7	CA	2.2	0.9	DK	27.3	4.8

Table: Impact induced by a 95*th* percentile coastal flood event (yearly damages) occurring in a single country. Results refer to the ten most impactful countries and the high-impact scenario at the horizon 2080 with and without adaptation. The direct impact corresponds to the value of direct damages induced by the event in the origin country, the global impact corresponds to the sum of direct and indirect losses in capital in the financial and private sectors of all countries.

Single country var-event

- Sizeable increase, among an approx. fixed pool of countries, in the scenario with constant protection standard.
- Order of magnitude increase in the scenario with historical protection: developed countries are hit and amplify massively the shocks because of financial leverage.

Compound event

- Independent realizations of shocks in each country.
- Evolution of the total distribution of damages.

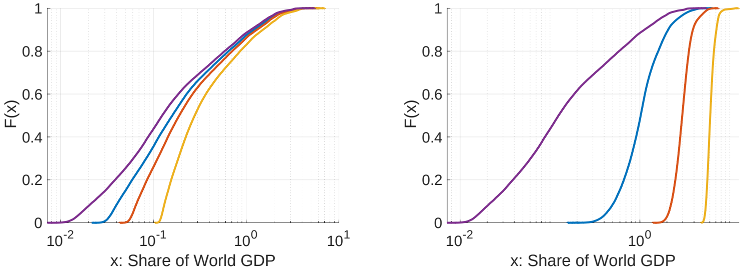
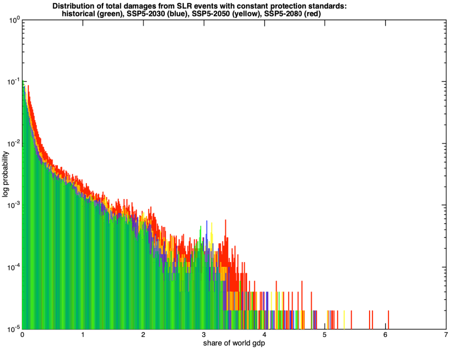
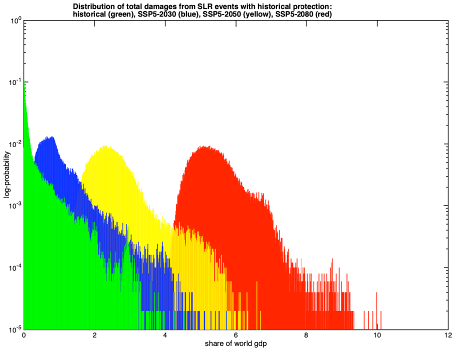


Figure: Empirical cumulative distribution of the global financial impact, including financial propagation, induced by coastal floods with (left) and without (right) adaptation for the high-impact scenario. Each panel displays the historical distribution of damages (purple), and the distribution under the high-impact scenario at horizons 2030 (blue), 2050 (red) and 2080 (yellow). Damages are measured in percentage of world gdp and empirical distribution is obtained from 50000 independent monte-carlo simulations in which damage realizations in each country are drawn independently.

Total impact with adaptation



Total impact without adaptation



Amplification of risk

- Ratio of risk-indicator with respect to historical values for selected impacts under SSP5-2080 scenario.

Indicator	Floods Constant protection	Floods Historical protection	SLR Constant protection	SLR Historical protection	Combined Constant protection	Combined Historical protection
Mean	1.4042876	8.1476014	1.5324597	17.153027	1.4667421	12.535679
Var-60	1.666253	15.020136	1.9800633	36.401347	1.6644206	16.772738
Var-70	1.64013	8.3245925	1.6989617	21.514085	1.5196233	12.214906
Var-80	1.2997226	4.9420639	1.4696438	11.887212	1.4099485	9.046179
Var-90	1.3520498	4.1915836	1.3520909	6.8085531	1.3827873	6.6060063
Var-95	0.8448927	1.3107112	1.2958635	4.7734885	1.3578035	5.1449014

- Increase in risk consistently observed across measures
- Largest impact on the mid-part of the right tail (60th-70th percentiles).

Sensitivity Analysis

- Main parameters of the model:
  - insurance buffer,
  - rate of transmission insurance-finance (γ),
  - total share covered (σ),
  - fiscal space,
  - max. sustainable debt.
- Major effects of σ and γ.

σ	0.25	0.5	0.75	1
SLR var-80	7.5244	6.6639	6.2205	5.2462
ρ	0.25	0.5	0.75	1
SLR var-80	5.3884	5.8312	6.2586	6.6639
$\overline{D}$ (% of GDP)	200	300	400	500
SLR var-80	7.5244	7.4989	7.4908	7.4862

Table: Impact on the value-at-risk at the 80th percentile (measured as share of world gdp) in the high-impact scenario without adaptation of variations in the value of the share σ of the shock covered (by the insurance and the governmental sector), the rate ρ of transmission of shocks from the insurance sector to the financial sector and of the maximal sustainable level of debt $\overline{D}$. Non-varying parameters are set to their default values.

Summary: distribution of impacts

- Larger impact on the tail of the distribution than on the mean.
- Adaptation is key:
  - With adaptation: 20% to 50 % increase in risk-level.
  - Without adaptation: order of magnitude increase in risk.

Summary: Allocation and propagation of impacts

- From the point of view of financial risk, the more buffers between the financial system and climate shocks there are, the better.
- From the domestic perspective:
  - Limit contagion from/Increase resilience of the insurance sector.
  - Government can act as a buffer if contagion less acute through government bonds.
- From the global perspective:
  - Require higher adaptation standards in countries with higher financial leverage.

Summary: Policy implications

- Required investments in adaptation.
- Capital requirements for the insurance sector (anticipating impacts of climate change).
- Insurance role of the government.
- Future climate impacts accounted for in investment decisions (capital requirements again)

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Intermission

A la semaine prochaine !

Outline

Components of transition risk

$$\text{RISK} = \text{EXPOSURE} \times \text{HAZARD} \times \text{VULNERABILITY}$$

1. Exposure: economic and financial assets in sectors directly or indirectly impacted by climate-policy.
2. Hazard: timing and intensity of climate policy
3. Vulnerability: impacts of climate policy shocks on asset value.

Climate policy: general equilibrium analysis

- General equilibrium model with L goods, n producers with production set $Y_j \in \mathbb{R}^L$, m consumers with utility $u_i : \mathbb{R}^L_+ \to \mathbb{R}_+$, initial endowment $e_i \in \mathbb{R}^L_+$, shares $\theta_{i,j} \in \mathbb{R}_+$.
- Equilibrium defined as price $p^* \in \mathbb{R}^L_+$, consumption plans $(x_i^*)_{i=1,\cdots m} \in (\mathbb{R}^L_+)^m$, production plans $(y_j^*)_{i=1,\cdots n} \in (\mathbb{R}^L_+)^n$ such that:
  - $\forall j = 1, \cdots n,\ y_j^* = \text{argmax}_{y_j \in Y_j} p^* \cdot y_j$
  - $\forall i = 1, \cdots m,\ x_i^* = \text{argmax}_{\{x_i \in \mathbb{R}^L_+ | p \cdot x_i \leq p \cdot e_i + \sum_j \theta_{i,j} p^* \cdot y_j^*} u_i(x_i)$
  - $\sum_{i=1}^m x_i^* = \sum_{j=1}^n y_j^* + \sum_{i=1}^m e_i$
- Production $y_j \in Y_j$ induces ghg emissions $f_j(y_j)$.

Climate policy: genenal equilibrium analysis

- Emissions unconstrained initially but climate policy induces, via market or tax, a cost q on emissions.
- New equilibrium given by $\overline{p}, (\bar{x}_i), (\bar{y}_j)$ such that:
  - $\forall j = 1, \cdots n,\ \bar{y}_j = \text{argmax}_{y_j \in Y_j} \overline{p} \cdot y_j - q f_j(y_j)$
  - $\forall i = 1, \cdots m,\ \bar{x}_i = \text{argmax}_{\{x_i \in \mathbb{R}^L_+ | \overline{p} \cdot x_i \leq \overline{p} \cdot e_i + \sum_j \theta_{i,j} \overline{p} \bar{y}_j - q f_j(\bar{y}_j)} u_i(x_i)$
  - $\sum_{i=1}^m \bar{x}_i = \sum_{j=1}^n \bar{y}_j + \sum_{i=1}^m e_i$
- N.B: initial equilibrium such that
  - $\forall j = 1, \cdots n,\ y_j^* = \text{argmax}_{y_j \in Y_j} p^* \cdot y_j$
  - $\forall i = 1, \cdots m,\ x_i^* = \text{argmax}_{\{x_i \in \mathbb{R}^L_+ | p \cdot x_i \leq p \cdot e_i + \sum_j \theta_{i,j} p^* \cdot y_j^*} u_i(x_i)$
  - $\sum_{i=1}^m x_i^* = \sum_{j=1}^n y_j^* + \sum_{i=1}^m e_i$
- General equilibrium effects: each actor potentially affected by carbon price.

Integrated assessment models

- Family of general-equilibirum integrated-assessment models (see https://www.iamcdocumentation.eu).
- Basics model à la Nordhaus

$$
\left\{
\begin{array}{ll}
\max_{(C_t,\mu_t)_{t=1,\cdots,T}} & W_t = \sum_{t=1}^{T}(1+\rho)^{-t} L_t \frac{[C_t/L_t]^{1-\alpha}}{1-\alpha} \\
s.t & \\
 & Q_t = I_t + C_t \\
 & K_t = I_t + (1-\delta)K_{t-1} \\
 & Q_t = \frac{\Omega_t}{1+\Omega_t}(1-\theta\mu_t^{\tau})A_t K_t^{\gamma} L_t^{1-\gamma} \\
 & \Omega_t = \psi_1 T_t + \psi_2 T_t^2 \quad \text{(“judgmental" calibration)} \\
 & E(t) = \sigma(t)(1-\mu(t))A_t K_t^{\gamma} L_t^{1-\gamma} \\
 & T_t = f((E_\nu)_{\nu \le t}) \quad \text{(climate module)}
\end{array}
\right.
$$

Integrated assessment models

- + exogenous constraints on emissions or temperature (climate policy).
- + detailed representation of energy input in production:

$$
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 & \max_t T_t \leq \overline{T}
\end{array}
\right.
$$

- + spatial structure (weighted average of regional utilites).

Representation of the production process in iams.

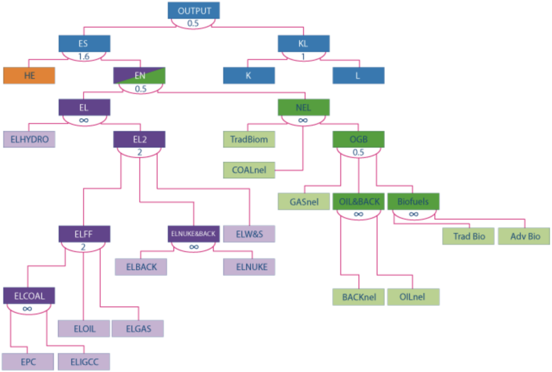


Figure: Schematic representation of the production process in the Witch model (source: www.iamcdocumentation.eu)

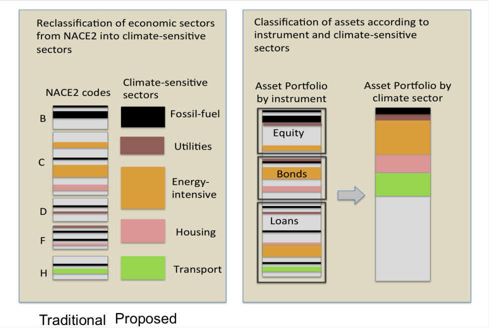
Usage of IAMs for climate policy assessment

- Variety of assumptions/models about technological structure and technological progress.
- Assess economic impacts of different climate policy scenarios: climate objective but also its international implementation.
- Relevant output: carbon price, market share of different (energy) subsectors in each country/region (link to CPRS)

Exposure: empirical perspective

- Structured micro-economic data on firms mostly available in the form of sectoral classification (NACE, NAICS, ISIC), not production function.
- Structure of the classification (aggregate categories) not appropriate to characterise exposure to climate policy, e.g. hard to distinguish energy sources or inputs to the fossil fuel industry.

Exposure: empirical perspective



- Climate-policy relevant sectors identified based on their GHG emissions, their role in the energy supply chain, and existence of related climate policy institutions.
- Remap standard classification of economic activities (NACE) into climate-policy relevant sectors (CPRS 1 and CPRS 2)

Exposure: portfolio analysis

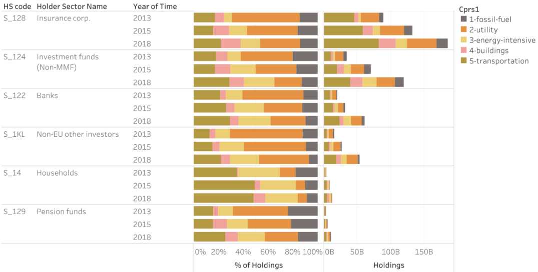


Figure: Breakdown of exposures by institutional sector and CPRS (level 1) through bonds. Source Battiston et al. for EU technical expert group on sustainable finance.

Exposure: portfolio analysis

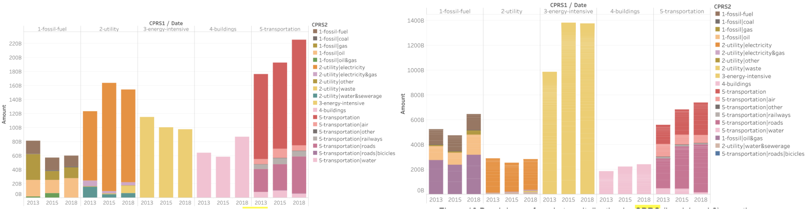


Figure: Breakdown of outstanding bond amount (left) and market capitalisation (right) from EU NFCs by CPRS (level 1 and 2) over time. Source Battiston et al. for EU technical expert group on sustainable finance.

Exposure: portfolio analysis

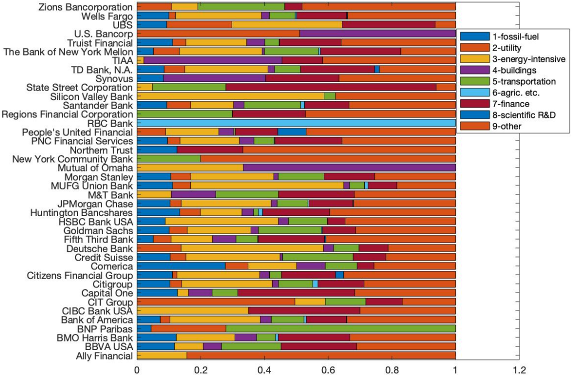


Figure: Breakdown of exposures in the syndicated loan portfolio of U.S banks and/or U.S. subsidiaries of international banks (dealscan data, Mandel et al. forthcoming).

Hazards: uncertainty about climate policy

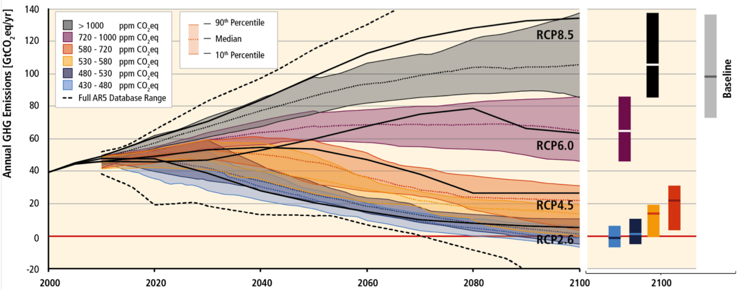


Figure: RCPs and associated uncertainties range for emission pathways

Hazard: economic assessment of climate policy

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$$

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\end{cases}
$$

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Representation of the production process in iams.

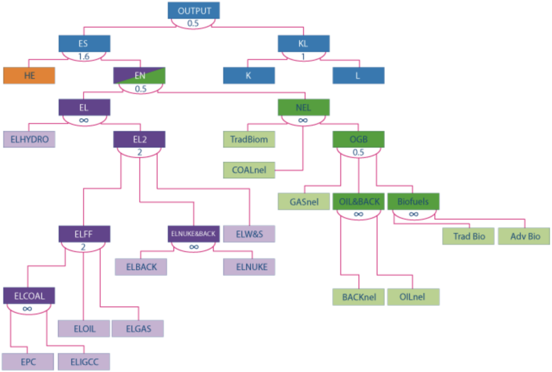
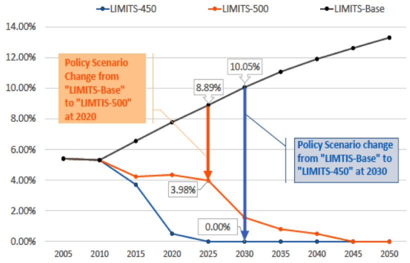


Figure: Schematic representation of the production process in the Witch model (source: www.iamcdocumentation.eu)

Usage of IAMs for climate policy assessment

- Variety of assumptions/models about technological structure and technological progress.
- Assess economic impacts of different climate policy scenarios: climate objective but also its international implementation.
- Relevant output: carbon price, market share of different (energy) subsectors in each country/region (link to CPRS)

Hazards: uncertainty about sectoral and geographical impacts



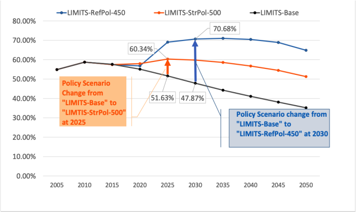


Figure: Market share of coal in Sub-Saharan Africa (left) and of renewables in Latin America (right) in secondary energy production for bau, 500ppm et 450ppm scenarios

Hazards quantified

- For each technology/subsector (e.g. Electricity|Fossil) k in a climate-policy relevant sector, each climate-policy scenario c and each date τ, iam models yield a shock $f(k, c, \tau)$ on the market share of the technology in case of a policy shift/disorderly transition to scenario c at date τ.
- Transition risk: impact on asset value ?
- Working assumption:*"The NGFS recognises that there is a strong risk that climate related financial risks are not fully reflected in asset valuation."*
- Problematic: how to integrate economic information in asset valuation ?

Vulnerability of asset values.

- Assuming a firm's asset values (i.e. asset side of the balance sheet) are proportional to market share, shock on corporate asset value determined by technological composition of its revenues, i.e. for $t \geq \tau$:

  $$A_t(c,\tau) = (1-s(c,\tau))\tilde{A}_t := \sum_{k \in \mathrm{CPRS}} w_k(1-f(k,c,\tau))\tilde{A}_t + (1-\sum_{k \in \mathrm{CPRS}} w_k)\tilde{A}_t$$

  where $\tilde{A}_t$ value of assets if market ignores climate shocks.
- N.B. Linear impact on asset value can be seen either as first-order approximation or “rationalized" by assuming (i) total market size not affected by the shock, (ii) value proportional to market share.
- N.B.2: this assumes that the market will not price the risk until it materializes.
- N.B.3: Rather than a deterministic shock, one can infer distribution of shocks from family of models.

Vulnerability of asset values.

- Given impact on firm's asset value, one can use structural credit risk model to assess impact on the value of its financial liabilities.
- e.g. Merton model assumes $d\tilde{A} = \tilde{A}(\mu_{\tilde{A}} dt + \sigma_{\tilde{A}} dW_t)$ and debt structure captured by zero-coupon debt of nominal L and maturity T. Then:
  - Debt valued as safe-claim minus European put $D_T = L - \max(L - \tilde{A}_T, 0)$.
  - Equity values a European call $E_T = \max(L - \tilde{A}_T, 0)$.

Vulnerability of asset values.

- In absence of climate-shocks, debt-value given by Black and Scholes formula.

$$D_t = L\exp(-r(T-t))N(d_-)+\tilde{A}_t N(d_+) \quad \text{where } d_\pm = \frac{\log(\tilde{A}_t/L)+(r\pm\sigma^2_{\tilde{A}}/2)}{\sigma_{\tilde{A}}\sqrt{T-t}}$$

- Following climate-shock (c,τ), assets are reevaluated

$$\begin{aligned}
\text{If } t<\tau: &\quad D_t(c,\tau) = D_t \\
\text{If } t\geq\tau: &\quad D_t(c,\tau) = L\exp(-r(T-t))N(d_-) + A_t(c,\tau)N(d_+) \\
&\quad \text{where } d_\pm = \frac{\log(A_t(c,\tau)/L)+(r\pm\sigma^2_{\tilde{A}}/2)}{\sigma_{\tilde{A}}\sqrt{T-t}}
\end{aligned}$$

- The latter the transition occurs the larger the gap to bridge to be aligned with the 2°C scenario and thus the larger the shock.

Micro-economic assumptions underlying the vulnerability model

- He and Leland (1993): setting with one unit risky asset and one riskless bond in zero-net supply (assume zero interest)
- Representative agent initially holds risky asset, chooses holding of risky asset through time $I(t)$, and consumes at final date T only.
- Diffusion process $d\tilde{A} = \tilde{A}(\mu_{\tilde{A}}dt + \sigma_{\tilde{A}}dW_t)$ is equilibrium asset-price if holding only risky asset is solution to

$$\left\{ \begin{array}{cc} \sup_{\mathcal{I}} & \mathbb{E}(U(X(T))) \\ s.t & dX(t) = \mu_{\tilde{A}} I(t)dt + \sigma_{\tilde{A}} I(t)dW_t \\ & X(t) \geq 0 \end{array} \right.$$

- Diffusion consistent with equilibrium if U exhibits constant-relative risk aversion and ${}^{XU''(X)}/_{U'(X)} = {}^{\mu_{\tilde{A}}}/_{\sigma^2_{\tilde{A}}}$.
- In particular, similar diffusion model can be consistent before and after shock

Treatment of ambiguity

- Even if scenario (e.g. 2°C scenario) is fixed, uncertainty about timing non-probabilistic.
- Decision under uncertainty:
- α- maxmin approach (Arrow and Hurwicz 1972, Gilboa and Schmeidler 1989, Jaffray and Philippe 1997, Ghirardato et al. 2004):

$$\overline{D}_t(\alpha) = \alpha \min_{(c,\tau)} D_t(c,\tau) + (1-\alpha) \max_{(c,\tau)} D_t(c,\tau)$$

- Smooth-amiguity approach à la Klibanoff et al. 2005:

$$\tilde{D}_t = \int_{(c,\tau)} \phi(D_T(c,\tau))\, d\pi(c,\tau)$$

Impact of uncertainty on asset valuation

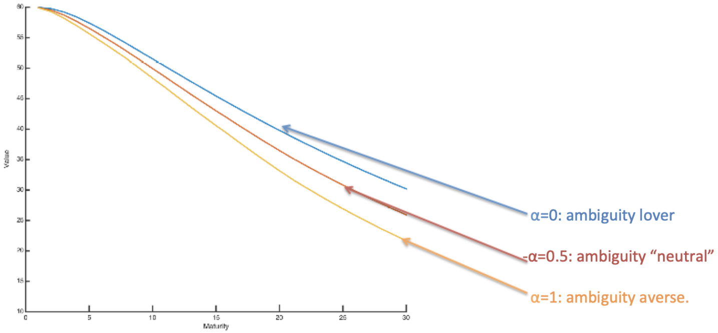


Figure: Impact of climate shocks on the value of a zero-coupon of face-value 60 for a composite emitter built proportionally to the composition of eurostoxx 60 oil and Gas for increasing maturity and varying levels of ambiguity aversion in the context of a transition to scenario LIMITS 450 (average shock over IAMs) .

Risk-equivalent impact of Climate Shocks

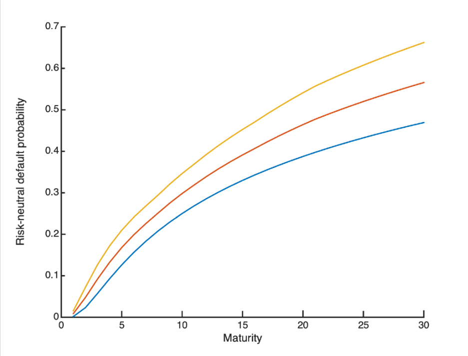


Figure: Impact of climate shocks on the risk-neutral probability of default of a zero-coupon of face-value 60 for a composite emitter built proportionally to the composition of eurostoxx 60 oil and Gas for increasing maturity and varying levels of ambiguity aversion. Gap widens with maturity as potential magnitude of climate shock increases

Impact of timing of Climate Shocks

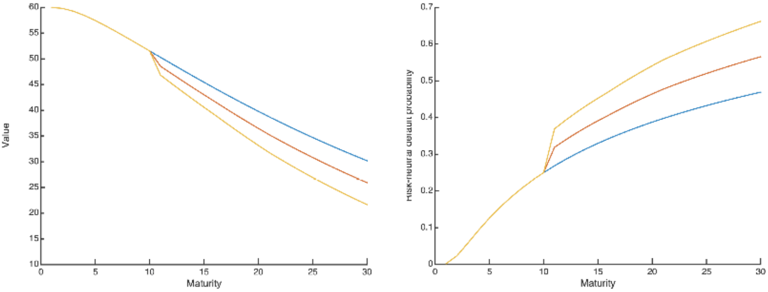


Figure: Value of debt (left) and risk-neutral default probability (right) when shock can't occur before period 10.

Impact of timing of Climate Shocks

Ticker	Company	Maxmin Change	0.5 Maxmin Change
'UN01 GR'	UNIPER	-14.52	-7.26
'ENG SM'	ENAGAS	-12.06	-6.03
'SRG IM'	SNAM SPA	-11.91	-5.95
'ENGI FP'	ENGIE	-10.96	-5.48
'FP FP'	TOTAL	-9.84	-4.92
'LUPE SS'	LUNDIN PETROLEUM	-9.45	-4.73
'HER IM'	HERA	-8.52	-4.26
'REP SM'	REPSOL	-0.67	-0.33
'A2A IM'	A2A	-0.06	-0.03
'ENI IM'	ENI	-0.05	-0.03
'VWS DC'	VESTAS	0.00	0.00
'ELE SM'	ENDESA	0.00	0.01
'NESTE FH'	NESTE	0.00	0.02
'EDF FP'	EDF	0.00	0.11
'FORTUM FH'	FORTUM	0.00	0.20
'NHY NO'	NORSK HYDRO	0.00	0.73
'REE SM'	RED ELECTRICA	0.00	1.06
'SGRE SM'	GAMESA	0.00	2.83
'TRN IM'	TERNA	0.00	4.28
'IBE SM'	IBERDROLA	0.00	6.63

Figure: percentage Impact on the value of 5 years zero-coupon of a transition to scenario LIMITS 450 (average shock over IAMs) for an ambiguity averse ($\alpha = 0.1$) and an ambiguity « neutral » ($\alpha = 0.5$) decision-maker. Sample of Stocks from EUROSTOXX Oil and Gas and Utilities (illustrative values).

Second-round effects: propagation of shocks

- Balance sheet of financial institution i at date t: $F_i(t) = \sum_{\{j \ | F_j(t)>0\}} B^f_{i,j}(t) - \sum_{j=1}^N L^f_{i,j} + B^e_i(t) - L^e_i$ where F_i is equity of bank i, $B^b_{i,j}$ (resp. $L^b_{i,j}$) interbank assets (resp. liability) and B^e_i (resp. L^e_i) interbank asset (resp. liability).
- Following a shock on external assets $B^e_i(1) < B^e_i(0)$.
- Propagation of shocks within the financial sector according to debtrank algorithm. For $t \geq 2$:
  - $F_i(t+1) = F_i(t) + \sum_{\{j \ | F_j(t)>0\}} B_{i,j}(t) - \sum_{\{j \ | F_j(t-1)>0\}} B_{i,j}(t-1)$
  - $B_{i,j}(t+1) = \dfrac{F_j(t)}{F_j(t-1)} B_{i,j}(t)$
- Given common shock s on value of external assets, girst-order approximation of shocks on bank i :

$$h(i) := \ell^e_i + \ell^b_i \ell^e$$

where $\ell^e_i = {}^{B^e_i}/F_i$ and $\ell^b_i = \sum_j {}^{B_{i,j}}/F_i$.

Structure of leverage

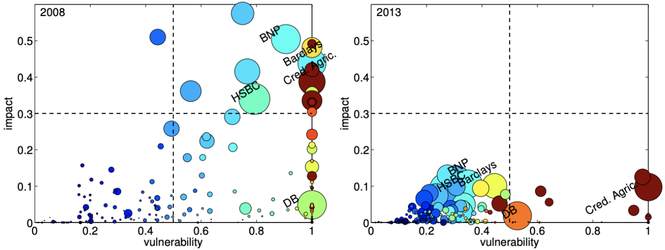


Figure: Vulnerability (to external shocks) vs Impact (on the system in case of default) in 2008 and 2013. Circle size reflects asset size, colors reflect the magnitude of the interbank leverage. The four quadrants divide the banks into four categories

Second-round effects

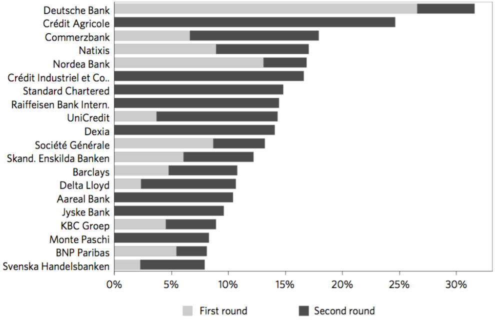


Figure 3 | First- and second-round losses in banks' equity for the 20 most-severely affected EU listed banks, under the Fossil fuel + Utilities 100% shock. Subsidiaries have not been taken into account.

Figure: First and Second round losses for 100% fossil+utilities shock. Source Battiston et al. 2017

Summary

- Concerns that the impacts of climate policy/transition risks are not reflected in asset valuation.
- Integrated assessment models can be used as a source of information on climate policy shocks.
- Economic assessment of climate policy shocks can be used as input to structural credit risk models under simplifying assumptions.
- Ambiguity/uncertainty about the timing and the stringency of climate policy can be captured through decision-theoretic models.
- Mostly empirical work, missing analytical framework bridging production theory to asset valuation

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Complements on ambiguity

- If $\mathbb{Q}$ denotes the risk-neutral probability inferred from market-data.
- α- maxmin approach:

$$\overline{D}_t(\alpha) = \alpha \min_{(c,\tau)} e^{-r(T-t)} \mathbb{E}_{\mathbb{Q}}[\min(L, (1-s(c,\tau))A_T] + (1-\alpha) \max_{(c,\tau)} e^{-r(}$$

- Smooth-amiguity approach

$$\tilde{D}_t = \int \phi \left(e^{-r(T-t)} \mathbb{E}_{\mathbb{Q}}[\min(L, (1-s(c,\tau))A_T] \right) \, d\pi(c,\tau)$$