# Course 2021-2022 in ESG and Climate Risks
# Lecture 4. Climate Risk

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February 2022

[1] The opinions expressed in this presentation are those of the authors and are not meant to represent the opinions or official positions of Amundi Asset Management.

# Agenda

- **Lecture 1: Introduction**
  - *Definition, Actors, the Market of ESG Investing* (42 slides)
- **Lecture 2: ESG Investing**
  - *ESG Scoring, ESG Ratings, Performance of ESG Investing, ESG Financing, ESG Premium* (132 slides)
- **Lecture 3: Other ESG Topics**
  - *Sustainable Financing Products, Impact Investing, Voting Policy & Engagement, ESG and Climate Accounting* (82 slides)
- **Lecture 4: Climate Risk**
  - *Definition, Global Warming, Economic Modeling, Risk Measures* (176 slides)
- **Lecture 5: Climate Investing**
  - *Portfolio Decarbonization, Net Zero Carbon Metrics, Portfolio Alignment* (164 slides)
- **Lecture 6: Mathematical Methods, Technical Tools and Exercises**
  - *Scoring System, Trend Modeling, Geolocation Data, Numerical Computations, Optimization* (150+ slides)

# General information

1. **Overview**
   The objective of this course is to understand the concepts of sustainable finance from the viewpoint of asset owners and managers
2. **Prerequisites**
   M1 Finance or equivalent
3. **ECTS**
   3
4. **Keywords**
   Finance, Asset Management, ESG, Responsible Investing, Climate Change
5. **Hours**
   Lectures: 18h
6. **Evaluation**
   Project + oral examination
7. **Course website**
   `http://www.thierry-roncalli.com/SustainableFinance.html`

# Class schedule

## Course sessions

- Date 1 (6 hours, AM+PM)
- Date 2 (6 hours, AM+PM)
- Date 3 (6 hours, AM+PM)

Class times: Friday 9:00am-12:00pm, 1:00pm–4:00pm, Location: University of Evry

# Additional materials

**http://www.thierry-roncalli.com/SustainableFinance.html**

- Slides
- Past examinations
- Exercises + Solutions
- LaTeX source of the slides + figures (in pdf format)
- Links to the references

# Main references

## Amundi publications on ESG Investing


1. Bennani *et al.* (2018), How ESG Investing Has Impacted the Asset Pricing in the Equity Market, DP-36-2018, 36 pages, November 2018
2. Drei *et al.* (2019), ESG Investing in Recent Years: New Insights from Old Challenges, DP-42-2019, 32 pages, December 2019
3. Ben Slimane *et al.* (2020), ESG Investing and Fixed Income: It's Time to Cross the Rubicon, DP-45-2019, 36 pages, January 2020
4. Roncalli, T. (2020), ESG & Factor Investing: A New Stage Has Been Reached, Amundi Viewpoint, May 2020


Available at `https://research-center.amundi.com` or `www.ssrn.com`

# Main references

## Amundi publications on Climate Investing

1. Le Guenedal, T. (2019), Economic Modeling of Climate Risk, WP-83-2019, 92 pages, April 2019
2. Bouchet, V., and Le Guenedal, T. (2020), Credit Risk Sensitivity to Carbon Price, WP-95-2020, 48 pages, May 2020
3. Le Guenedal *et al.* (2020), Trajectory Monitoring in Portfolio Management and Issuer Intentionality Scoring, WP-97-2020, 54 pages, May 2020
4. Roncalli *et al.* (2020), Measuring and Managing Carbon Risk in Investment Portfolios, WP-99-2020, 67 pages, August 2020
5. Ben Slimane, M., Da Fonseca, D., and Mahtani, V. (2020), Facts and Fantasies about the Green Bond Premium, WP-102-2020, 52 pages, December 2020
6. Le Guenedal, Drobinski, P., and Tankov, P. (2021), Measuring and Pricing Cyclone-Related Physical Risk under Changing Climate, WP-111-2021, 42 pages, June 2021
7. Adenot *et al.* (2022), Cascading Effects of Carbon Price through the Value Chain and their Impacts on Firm's Valuation, WP-122-2022, 82 pages, February 2022
8. Le Guenedal *et al.* (2022), Net Zero Carbon Metrics, WP-123-2022, 82 pages, February 2022

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# Main references

## Amundi ESG Thema


1. Créhalet, E. (2021), Introduction to Net Zero, *Amundi ESG Thema #1*, https://research-center.amundi.com
2. Créhalet, E., Foll, J., Haustant, P., and Hessenberger, T. (2021), Carbon Offsetting: How Can It Contribute to the Net Zero Goal?, *Amundi ESG Thema #5*, https://research-center.amundi.com
3. Créhalet, E., and Talwar, S. (2021), Carbon-efficient Technologies in the Race to Net Zero, *Amundi ESG Thema #6*, https://research-center.amundi.com
4. Le Meaux, C., Le Berthe, T., Jaulin, T., Créhalet, E., Jouanneau, M., Pouget-Abadie, T., and Elbaz, J. (2021), How can Investors Contribute to Net Zero Efforts?, *Amundi ESG Thema #3*, https://research-center.amundi.com


Available at https://research-center.amundi.com or www.ssrn.com

# Main references

## Academic publications

1. Andersson, M., Bolton, P., and Samama, F. (2016), Hedging Climate Risk, *Financial Analysts Journal*, www.ssrn.com/abstract=2499628.
2. Ardia, D., Bluteau, K., Boudt, K., and Inghelbrecht, K. (2021), Climate Change Concerns and the Performance of Green versus Brown Stocks, *National Bank of Belgium, Working Paper*, www.ssrn.com/abstract=3717722.
3. Battiston, S., Mandel, A., Monasterolo, I., Schütze, F., and Visentin, G. (2017), A Climate Stress-test of the Financial System, *Nature Climate Change*, www.ssrn.com/abstract=2726076.
4. Berg, F. Koelbel, J.F., and Rigobon, R. (2019), Aggregate Confusion: The Divergence of ESG Ratings, *Working Paper*, www.ssrn.com/abstract=3438533
5. Berg, F., Fabisik, K., and Sautner, Z. (2021), Is History Repeating Itself? The (Un)predictable Past of ESG Ratings , *Working Paper*, www.ssrn.com/abstract=3722087
6. Bolton, P., and Kacperczyk, M. (2021), Do Investors Care about Carbon Risk?, *Journal of Financial Economics*, www.ssrn.com/abstract=3594189
7. Bolton, P., Kacperczyk, M., and Samama, F. (2021), Net-Zero Carbon Portfolio Alignment, *Working Paper*, www.ssrn.com/abstract=3922686
8. Coqueret, G. (2021), Perspectives in ESG Equity Investing, *Working Paper*, www.ssrn.com/abstract=3715753

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## Academic publications


9. Crifo, P., Diaye, M.A., and Oueghlissi, R. (2015), Measuring the Effect of Government ESG Performance on Sovereign Borrowing Cost, *Quarterly Review of Economics and Finance*, hal.archives-ouvertes.fr/hal-00951304v3
10. Dennig, F., Budolfson, M.B., Fleurbaey, M., Siebert, A., and Socolow, R.H. (2015), Inequality, Climate Impacts on the Future Poor, and Carbon Prices, *Proceedings of the National Academy of Sciences*, www.pnas.org/content/112/52/15827
11. Engle, R.F., Giglio, S., Kelly, B., Lee, H., and Stroebel, J. (2020), Hedging Climate Change News, *Review of Financial Studies*, www.ssrn.com/abstract=3317570
12. Görgen, M., Jacob, A., Nerlinger, M., Riordan, R., Rohleder, M., and Wilkens, M. (2020), Carbon Risk, *Working Paper*, www.ssrn.com/abstract=2930897
13. Harris, J. (2015), The Carbon Risk Factor, *Working Paper*, www.ssrn.com/abstract=2666757
14. Karydas, C., and Xepapadeas, A. (2021), Climate Change Financial Risks: Implications for Asset Pricing and Interest Rates, *Working Paper*
15. Le Guenedal, T., and Roncalli, T. (2022), Portfolio Construction and Climate Risk Measures, *Climate Investing*, www.ssrn.com/abstract=3999971

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16. Martellini, L., and Vallée, L. (2021), Measuring and Managing ESG Risks in Sovereign Bond Portfolios and Implications for Sovereign Debt Investing, *Journal of Portfolio Management*, `www.risk.edhec.edu/measuring-and-managing-esg-risks-sovereign-bond`
17. Pedersen, L.H., Fitzgibbons, S., and Pomorski, L. (2021), Responsible Investing: The ESG-Efficient Frontier, *Journal of Financial Economics*, `www.ssrn.com/abstract=3466417`
18. Pástor, L., Stambaugh, R.F., and Taylor, L.A. (2021), Sustainable Investing in Equilibrium, *Journal of Financial Economics*, `www.ssrn.com/abstract=3498354`
19. Roncalli, T., Le Guenedal, T., Lepetit, F., Roncalli, T., and Sekine, T. (2021), The Market Measure of Carbon Risk and its Impact on the Minimum Variance Portfolio, *Journal of Portfolio Management*, `www.ssrn.com/abstract=3772707`
20. Van der Beck, P. (2021), Flow-driven ESG returns, *Working Paper*, `www.ssrn.com/abstract=3929359`

# Prologue

*"There is no Plan B, because there is no Planet B"*

Ban Ki-moon, UN Secretary-General, September 2014

**Is it a question of climate-related issues?**

**In fact, it is more an economic growth issue**

*"The Golden Rule of Accumulation: A Fable for Growthmen"*

Edmund Phelps, *American Economic Review*, 1961
Nobel Prize in Economics, 2006

# Climate risks and financial losses

## Climate risks transmission channels to financial stability

- The **physical risks** that arise from the increased frequency and severity of climate and weather related events that damage property and disrupt trade
- The **liability risks** stemming from parties who have suffered loss from the effects of climate change seeking compensation from those they hold responsible
- The **transition risks** that can arise through a sudden and disorderly adjustment to a low carbon economy

Speech by Mark Carney at the International Climate Risk Conference for Supervisors, Amsterdam, April 6, 2018

Physical and transition risks $\Leftrightarrow$ E

Liability risks $\Leftrightarrow$ S (and G ?)

# Climate risks and financial risks

**Risks are transversal to financial risks**

- **Carbon risk** (reputational and regulation risks) $\Rightarrow$ economic, market and credit risks
- **Climate risk** (extreme weather events, natural disasters) $\Rightarrow$ economic, operational, credit and market risks

Carbon/climate risks are part of risk management

# Some definitions

## Climate risk(s)

Climate risks include transition risk and physical risks:

- Transition risk is defined as the financial risk associated with the transition to a low-carbon economy. It includes policy changes, reputational impacts, and shifts in market preferences, norms and technology
- Physical risk is defined as the financial losses due to extreme weather events and climate disasters like flooding, sea level rise, wildfires, droughts and storms

# Some definitions

**Global warming ($\approx$ climate change)**

Global warming is the long-term heating of Earth's climate system observed since the pre-industrial period (between 1850 and 1900) due to human activities, primarily fossil fuel burning

NASA Global Climate Change — `https://climate.nasa.gov`

# Some definitions

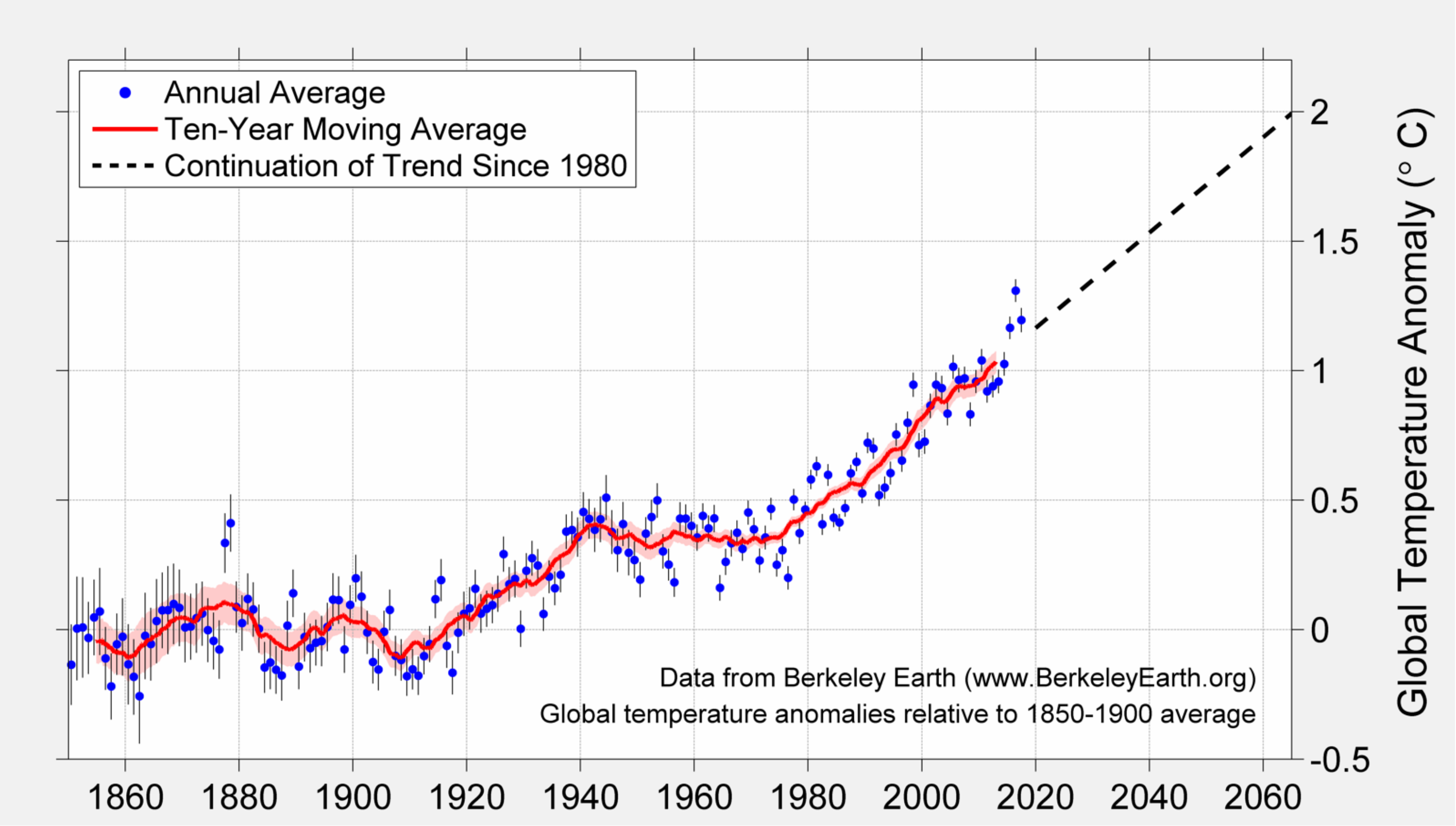



Figure 1: Global temperature anomaly

Source: Berkeley Earth (2018), `http://berkeleyearth.org`

# Some definitions

**Carbon risk**

Carbon risks correspond to the potential financial losses due to greenhouse gas (or GHG) emissions, mainly $CO_2$ emissions (in a strengthening regulatory context)

# Some definitions

## GHG

Greenhouse gases absorb and emit radiation energy, causing the greenhouse effect[a]:

1. Water vapour ($H_2O$)
2. Carbon dioxide ($CO_2$)
3. Methane ($CH_4$)
4. Nitrous oxide ($N_2O$)
5. Ozone ($O_3$)

[a] Without greenhouse effect, the average temperature of Earth's surface would be about $-18^\circ\mathrm{C}$. With greenhouse effect, the current temperature of Earth's surface is about $+15^\circ\mathrm{C}$.

# Some definitions

Table 1: Pros and cons of greenhouse gases

| GHG | Pros | Cons | Global warming |
|---|---|---|---|
| Water vapour | Life | | |
| Carbon dioxide | Photosynthesis | Pollution | ✓ |
| Methane | Energy | Explosive[2] | ✓ |
| Nitrous oxide | Dentist ☺ | | ✓ |
| Ozone | UV rays | | |

[2] And dangerous for human life

# Some definitions

### Carbon equivalent

Carbon dioxide equivalent (or $CO_2e$) is a term for describing different GHG in a common unit

- A quantity of GHG can be expressed as $CO_2e$ by multiplying the amount of the GHG by its global warming potential (GWP)
- 1 kg of carbone dioxide corresponds to 1 kg of $CO_2$
- 1 kg of methane corresponds to 25 kg of $CO_2$
- 1 kg of nitrous oxide corresponds to 310 kg of $CO_2$

In what follows, we use $CO_2$ in place of $CO_2e$

# $CO_2$ emissions

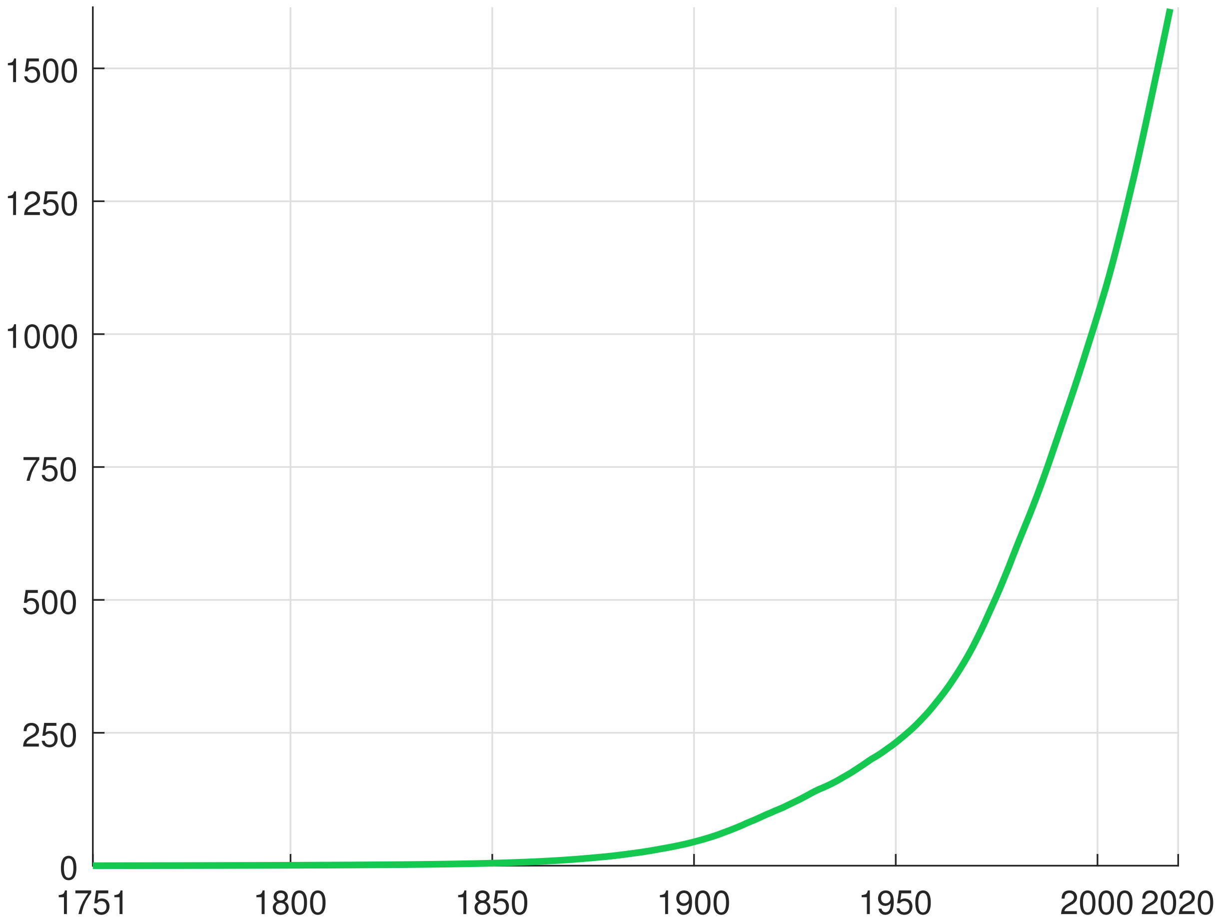



Figure 2: Cumulative $CO_2$ emissions (in $GtCO_2e$)

Source: Data on $CO_2$ and GHG Emissions by Our World in Data (https://github.com/owid/co2-data)

# $CO_2$ emissions

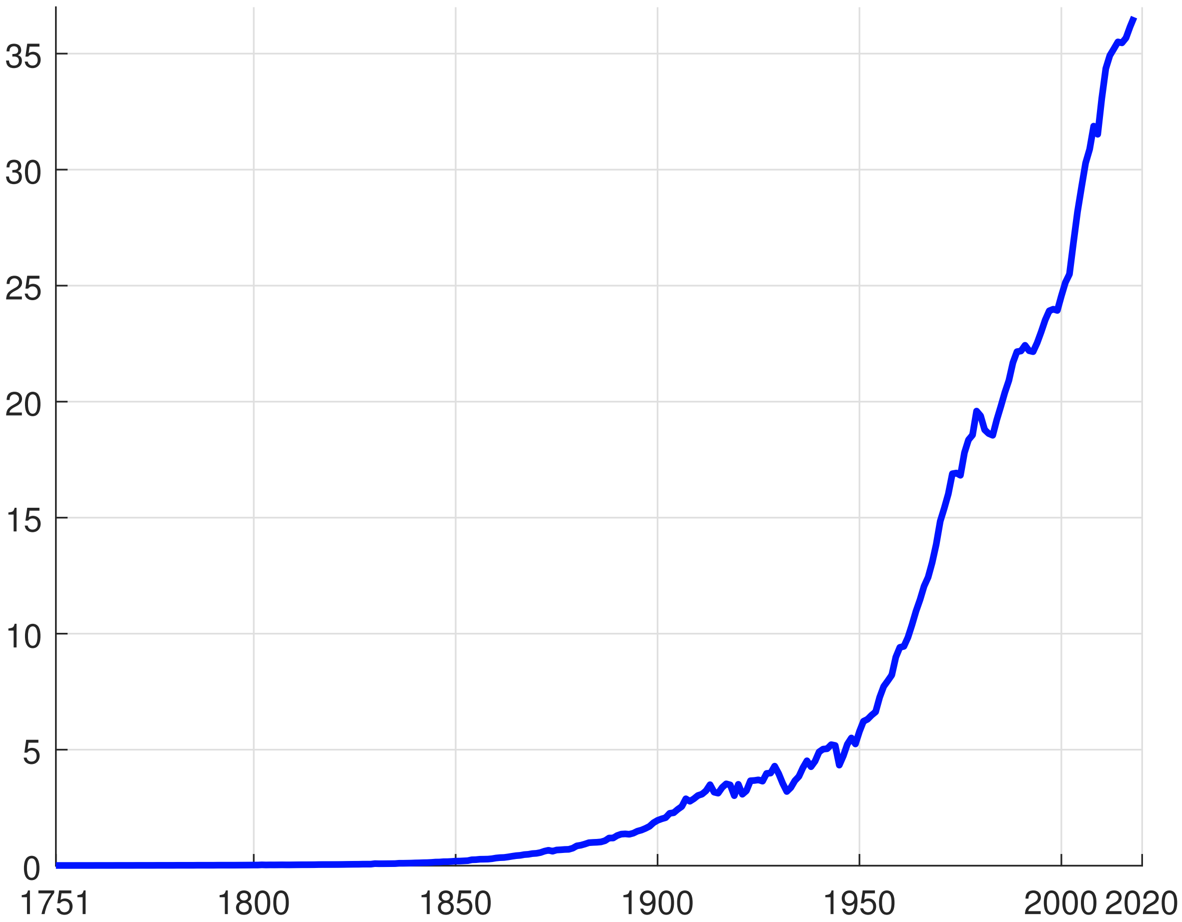



Figure 3: Annual $CO_2$ emissions (in $GtCO_2e$)

Source: Data on $CO_2$ and GHG Emissions by Our World in Data (`https://github.com/owid/co2-data`)

# $CO_2$ emissions

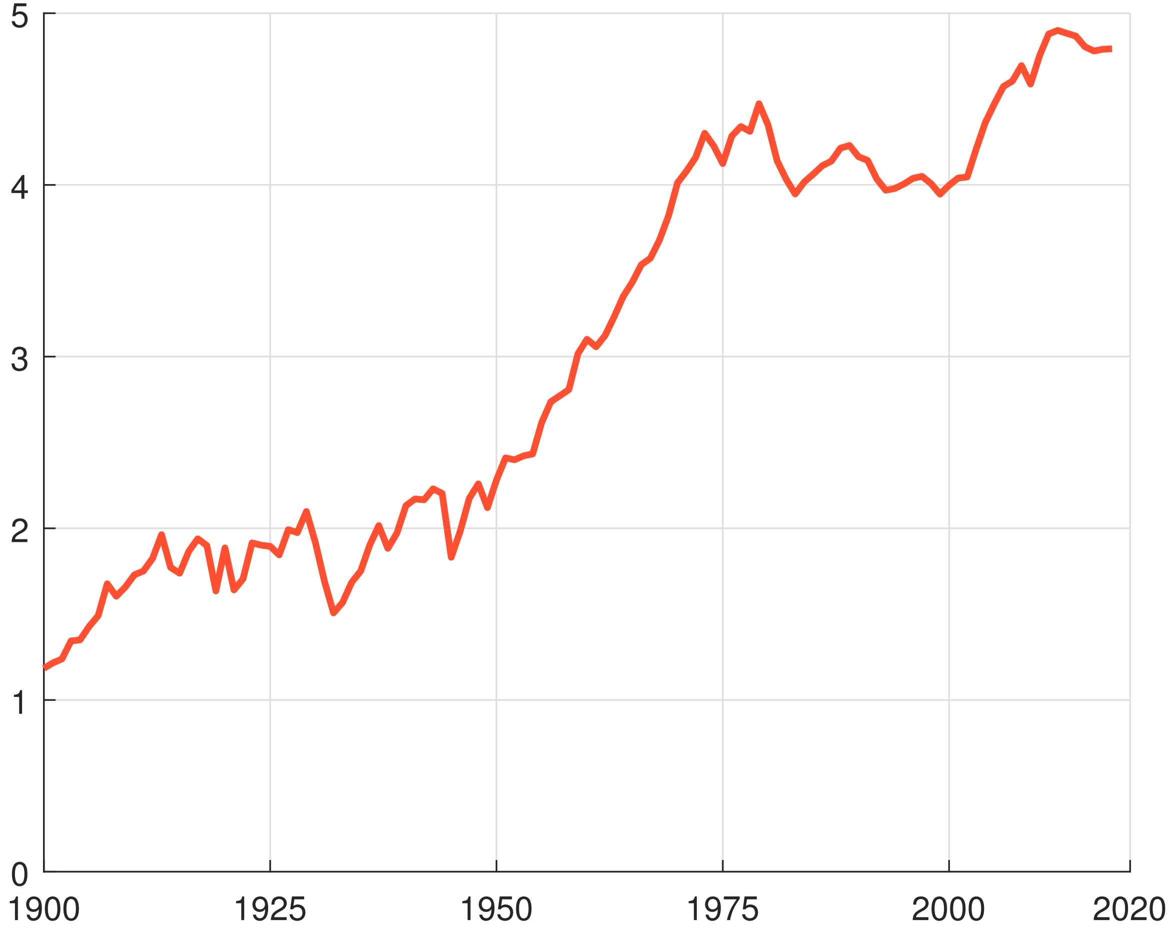



Figure 4: $CO_2$ emissions per capita (in tons per capita)

Source: Data on $CO_2$ and GHG Emissions by Our World in Data (`https://github.com/owid/co2-data`)

# $CO_2$ emissions

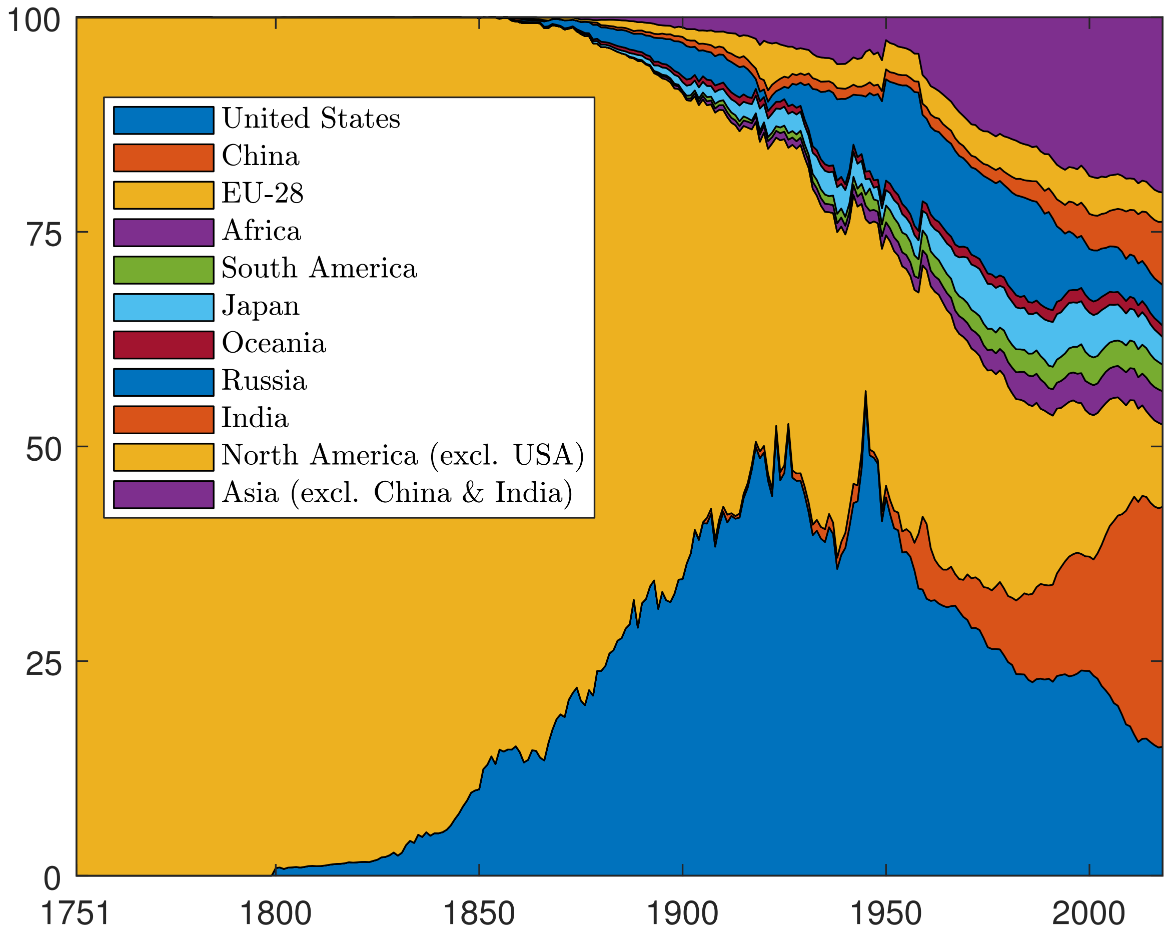
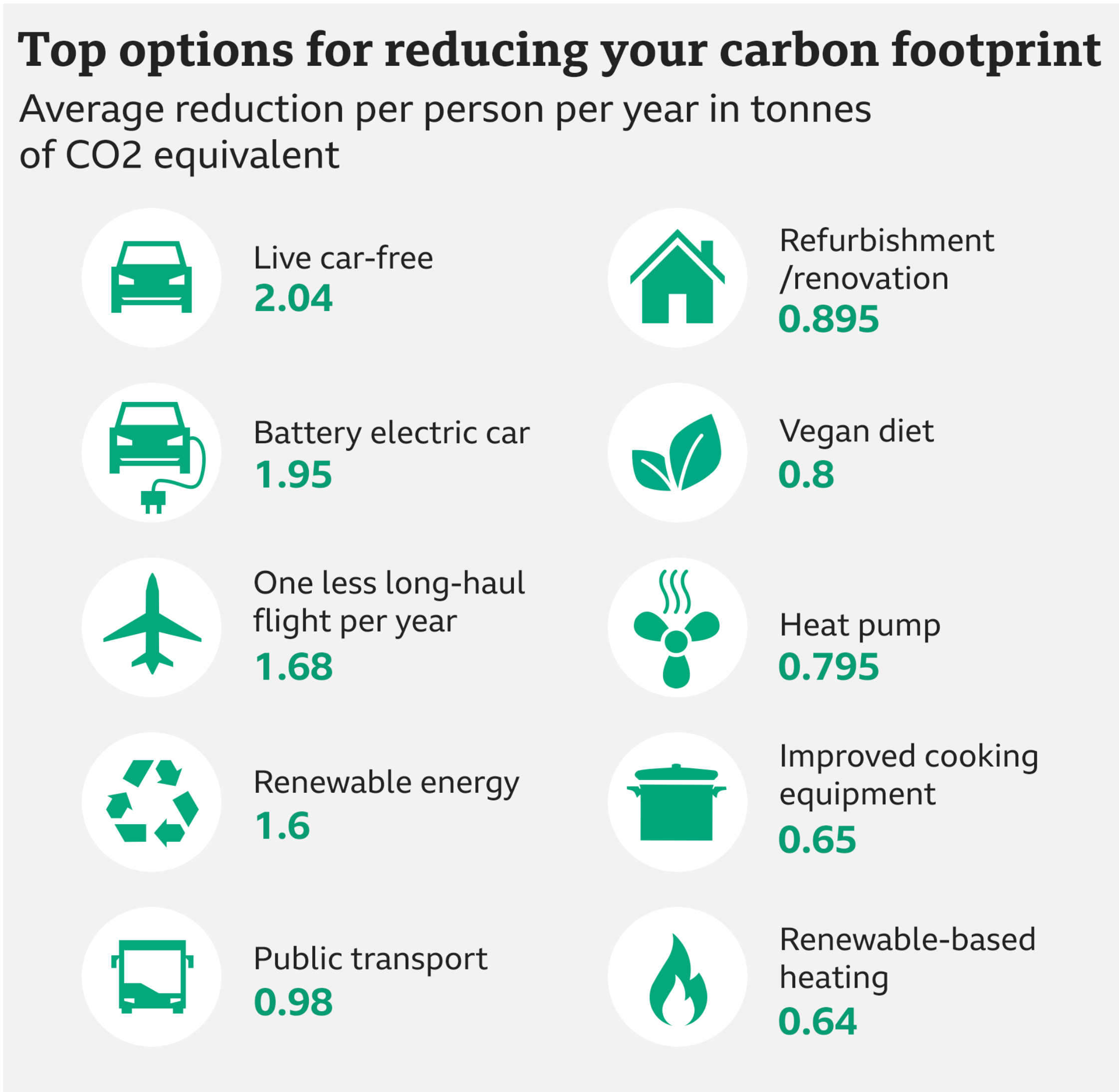



Figure 5: Share of $CO_2$ emissions (in %)

Source: Data on $CO_2$ and GHG Emissions by Our World in Data (`https://github.com/owid/co2-data`)

# $CO_2$ emissions




Source: Centre for Research into Energy Demand Solutions

BBC

# IPCC

- The Intergovernmental Panel on Climate Change (IPCC) is the United Nations body for assessing the science related to climate change
- The IPCC was created to provide policymakers with regular scientific assessments on climate change, its implications and potential future risks, as well as to put forward adaptation and mitigation options
- Website: `https://www.ipcc.ch`

**Remark**

IPCC is known as "*Groupe d'experts intergouvernemental sur l'évolution du climat*" (GIEC) in French

⇒ Other international bodies: International Energy Agency (IEA), etc.

# Scientific evidence of global warming: a rocky road

- 1824: Joseph Fourier published the scientific article "*Remarques générales sur les températures du globe terrestre et des espaces planétaires*" ⇒ the greenhouse effect
- 1863: John Tyndall published the books "*Heat Considered as a Mode of Motion*" in 1863 and "*Contributions to Molecular Physics in the Domain of Radiant Heat*" in 1872
- 1896: Svante Arrhenius published the scientific article "*On the Influence of Carbonic Acid in the Air upon the Temperature of the Ground*" ⇒ if the quantity of carbonic acid increases in geometric progression, the augmentation of the temperature will increase nearly in arithmetic progression
- 1958: Charles David Keeling started collecting carbon dioxide samples at the Mauna Loa Observatory (Hawai) ⇒ Keeling curve
- 2021: Klaus Hasselmann and Syukuro Manabe won the Nobel Prize in Physics for the physical modelling of Earth's climate, quantifying variability and reliably predicting global warming

# Scientific evidence of global warming: a rocky road

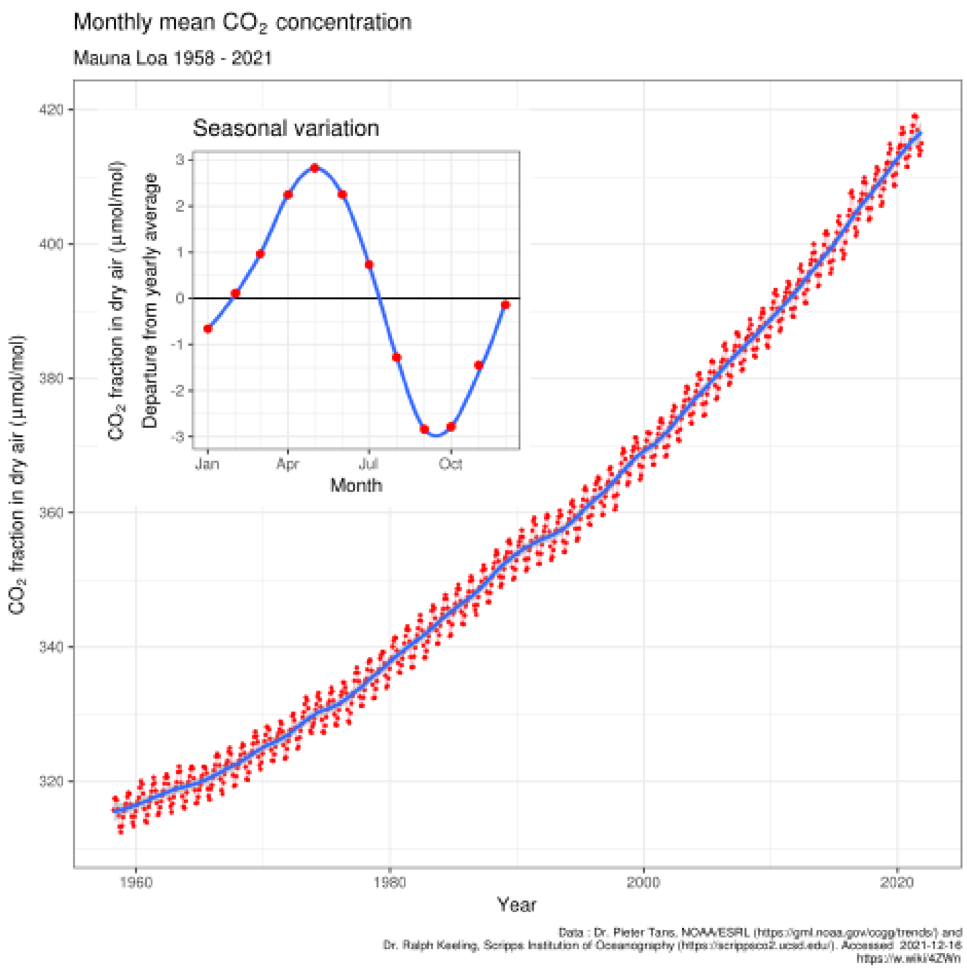



Figure 6: Keeling curve

Source: `https://en.wikipedia.org/wiki/Keeling_Curve`.

# IPCC

**Past**

- Global sea level rose by 19 cm over the period 1901-2010
- Global glacier volume loss is equivalent to 400 bn tons per year since 30 years

**Future**

- Global sea level could increase by 82 cm by 2100
- Global glacier volume could decrease by 85% by 2100

IPCC, Climate Change Synthesis Report (2014)

# IPCC

## IPCC working groups

- The IPCC Working Group I (WGI) examines the physical science underpinning past, present, and future climate change
- The IPCC Working Group II (WGII) assesses the impacts, adaptation and vulnerabilities related to climate change
- The IPCC Working Group III (WGIII) focuses on climate change mitigation, assessing methods for reducing greenhouse gas emissions, and removing greenhouse gases from the atmosphere

# IPCC

## Some famous reports

- IPCC Fifth Assessment Report (AR5): Climate Change 2014 — www.ipcc.ch/report/ar5
- Global Warming of 1.5°C — www.ipcc.ch/sr15
- IPCC Sixth Assessment Report (AR6): Climate Change 2022 — www.ipcc.ch/report/sixth-assessment-report-cycle

# IPCC scenarios

- Website: `https://www.ipcc.ch/data`
- The IPCC AR5 scenarios database comprises **31** models and in total **1 184** scenarios
- 4 reference scenarios: **representative concentration pathways** (RCP)
- Each RCP represents one possible evolution profile of GHG concentrations
  - RCP 2.6: $CO_2$ emissions start declining by 2020 and go to zero by 2100
  - RCP 4.5: $CO_2$ emissions peak around 2040, then decline
  - RCP 6.0: $CO_2$ emissions peak around 2080, then decline
  - RCP 8.5: $CO_2$ emissions continue to rise throughout the 21st century
- For each RCP, socio-economic development scenarios and various adaptation and mitigation strategies are associated
- They are called the **shared socioeconomic pathways** (SSP)

# IPCC scenarios

| RCP | Model | Contact |
|---|---|---|
| RCP 2.6 | IMAGE | Detlef van Vuuren (detlef.vanvuuren@pbl.nl) |
| RCP 4.5 | MiniCAM | Katherine Calvin (katherine.calvin@pnnl.gov) |
| RCP 6.0 | AIM | Toshihiko Masui (masui@nies.go.jp) |
| RCP 8.5 | MESSAGE | Keywan Riahi (riahi@iiasa.ac.at) |

Table 2: Associated model for each RCP

# IPCC scenarios

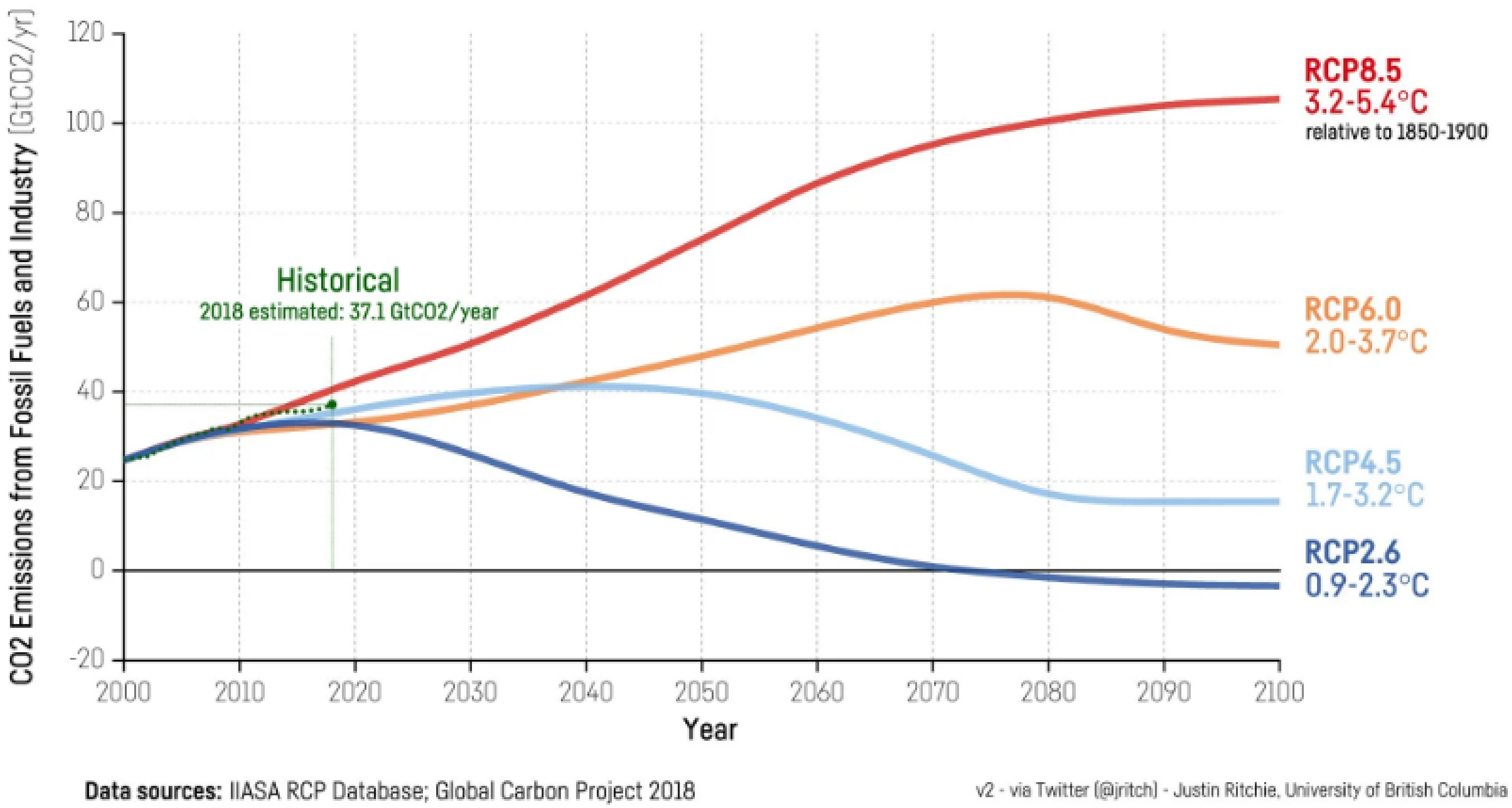



Figure 7: IPCC RCP scenarios: $CO_2$ emissions from fossil fuels and industry

# Carbon neutrality

**Carbon neutrality** (or net zero) means that any CO2 released into the atmosphere from human activity is balanced by an equivalent amount being removed

Apple Commits to Become Carbon Neutral to by 2030
(`https://www.bbc.com/news/technology-53485560`)

# Carbon dioxide removal

## Carbon dioxide removal (CDR)

1. Nature-based solutions
   - Afforestation (creating new forests)
   - Reforestation (multiplying trees in old forests)
   - Restoration of peat bogs
   - Restoration of coastal and marine habitats
2. Enhanced natural processes
   - Land management and no-till agriculture, which avoids carbon release through soil disturbance
   - Better wildfire management
   - Ocean fertilisation to increase its capacity to absorb $CO_2$ (enhanced weathering)
3. Technology solutions
   - Bioenergy with carbon capture and storage (BECCS)
   - Direct air capture (DAC)
   - Carbon mineralization

# Carbon dioxide removal

## The example of peatlands

- Peatlands are the largest natural terrestrial carbon store
- The term "*peatland*" refers to peat soil and wetland habitats
- They cover only 3% of the Earth's surface
- They store 600 $GtCO_2e$
  - $\approx$ 45% of all soil carbon
  - $\approx$ 67% of all atmosphere carbon
- A depth of one meter corresponds to 1 000 years of carbon storage
- Natural peatlands store 0.37 $GtCO_2e$ per year

Two issues:

1. Stopping the destruction
2. Restoring and rebuilding

# Carbon offsetting

Carbon offsetting $\neq$ carbon emissions reduction

## Definition

*"Carbon offsetting consists for an entity in compensating its own carbon emissions by providing for emissions reductions outside its business boundaries [...] It allows an entity to claim carbon reductions from projects financed either directly or indirectly through carbon credits" (Créhalet, 2021).*

# Carbon offsetting

Carbon offsetting mechanisms:

Suppliers of carbon offsets

⬇

Carbon credits

⬇

Purchasers of carbon offsets

⇒ Many issues: carbon credit issuance, double counting, leakage, certification, etc.

Examples with **REDD+** projects:

- **R**educing **E**missions from **D**eforestation and **F**orest **D**egradation
- What will happen if the forest has burned down?
- Issues of land management (afforestation in one area can lead to a deforestation in another area)

# The shared socioeconomic pathways

- **SSP1**: Low challenges for both mitigation and adaptation, rapid development: **Sustainability** (Taking the Green Road)
- **SSP2**: Moderate challenges for mitigation and adaptation: **Middle of the Road**
- **SSP3**: High challenges for both mitigation and adaptation — Concern about competitiveness, security and regional conflict pushing countries to focus on regional issues: **Regional Rivalry** (a Rocky Road)
- **SSP4**: Low challenges for mitigation high for adaptation — Unequal investment in human capital, concentration of power in a small business elite: **Inequality** (A Divided Road)
- **SSP5**: High challenge for mitigation low for adaptation: **Fossil-fueled Development** (Taking the Highway)

Figure 8: The shared socioeconomic pathways

Source: O'Neill *et al.* (2016)

# The shared socioeconomic pathways

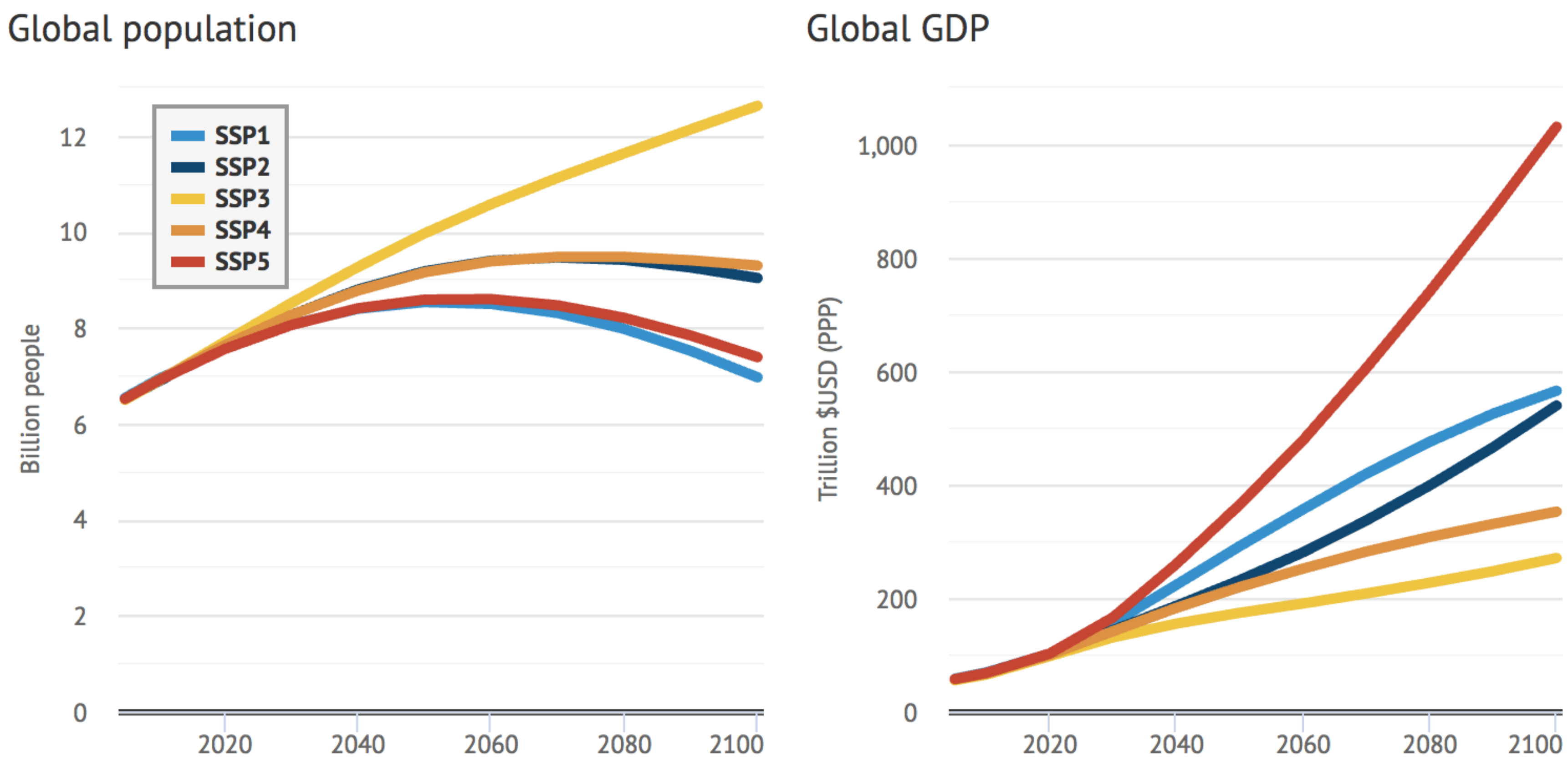



Figure 9: Projections of population and economic growth across SSP

Source: https://www.carbonbrief.org/explainer-how-shared-socioeconomic-pathways-explore-future-climate-change

# The shared socioeconomic pathways

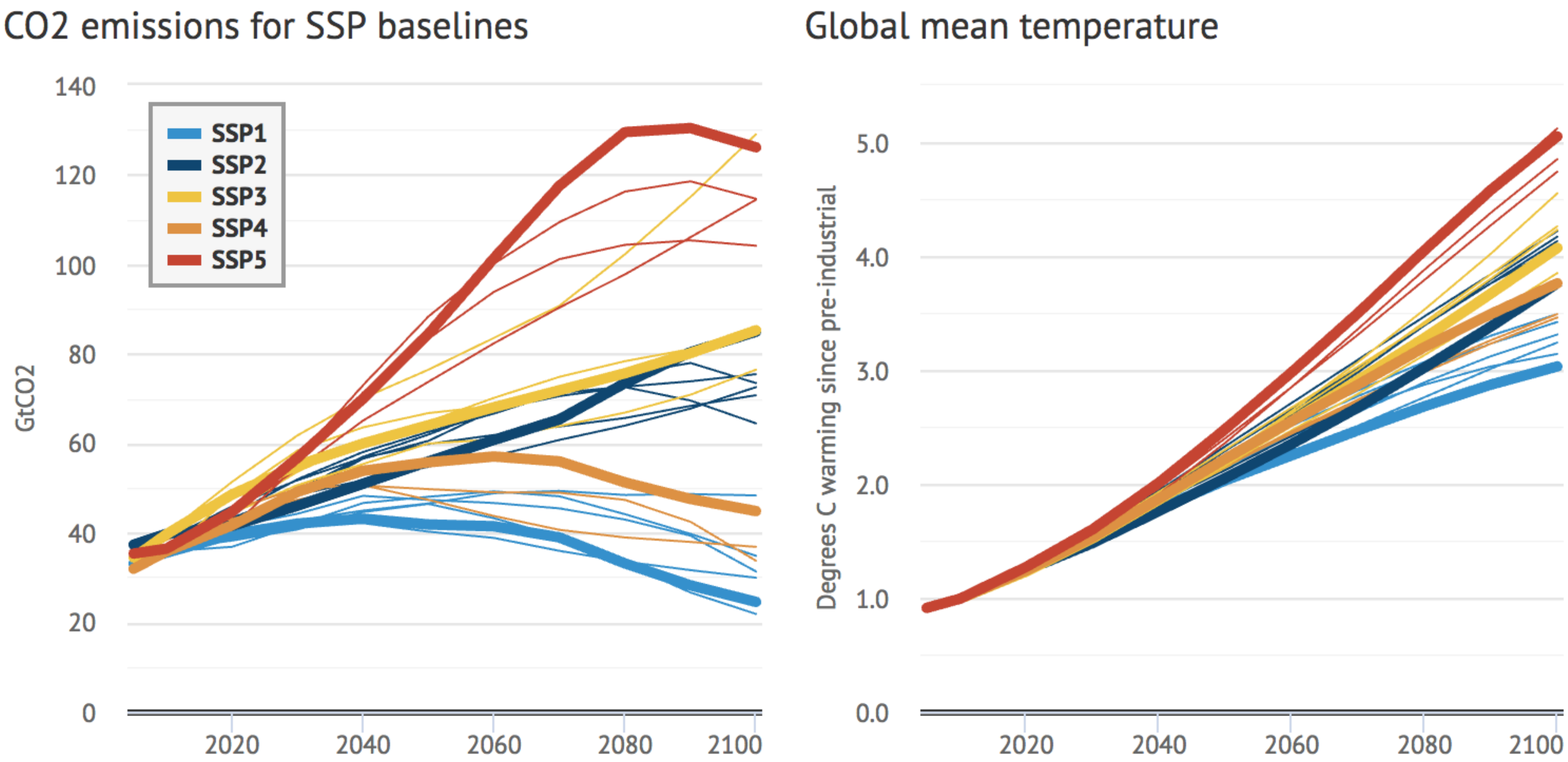



Figure 10: Projections of $CO_2$ emissions and temperatures across SSP

Source: https://www.carbonbrief.org/explainer-how-shared-socioeconomic-pathways-explore-future-climate-change

# Climate risk and missing factors

## The example of permafrost

- The permafrost contains 1 700 billion tons of carbon, almost double the amount of carbon that is currently in the atmosphere.
- Arctic permafrost holds roughly 15 million gallons of mercury – at least twice the amount contained in the oceans, atmosphere and all other land combined.
- A global temperature rise of $1.5^\circ C$ above current levels would be enough to start the thawing of permafrost in Siberia.
- The global warming will become out-of-control after this tipping point.
- The thawing of the permafrost also threatens to unlock disease-causing viruses long trapped in the ice.

$\Rightarrow$ The survival of Humanity becomes uncertain if the tipping point is reached

# Regulation of climate risk

- UN, international bodies & coalitions
- Countries
- Cities
- Industry self-regulation
- Non-governmental organizations (NGO)
- Financial regulators

**Hard regulation** $\neq$ **soft regulation**

# Regulation of climate risk

## UN

### United Nations Climate Change Conference

- Conference of the Parties (COP)
- Dealing with climate change
- COP 1: Berlin (1995)
- COP 3: Kyoto (1997) ⇒ Kyoto Protocol (CMP)
- COP 21: Paris (2015) ⇒ Paris Agreement (CMA)
- COP 26: Glasgow (November 2021)

# Regulation of climate risk

## UN

The **Kyoto Protocol** is an international treaty that commits state parties to reduce GHG emissions, based on the scientific consensus that:

1. **Global warming is occurring**
2. It is likely that **human-made $CO_2$ emissions have caused it**

# Regulation of climate risk

## UN

The **Paris Agreement** is an international treaty with the following goals:

1. Keep a global temperature rise this century well below $2^{\circ}\mathrm{C}$ above the pre-industrial levels
2. Pursue efforts to limit the temperature increase to $1.5^{\circ}\mathrm{C}$
3. Increase the ability of countries to deal with the impacts of climate change
4. Make finance flows consistent with low GHG emissions and climate-resilient pathways

$\Rightarrow$ Nationally determined contributions (NDC)

# Regulation of climate risk
## UN

Table 3: $CO_2$ emissions by country

| Rank | Country | $CO_2$ emissions Total (in GT) | Share | $CO_2$ emissions Per capita (in MT) |
|---|---|---|---|---|
| 1 | China | 10.06 | 28% | 7.2 |
| 2 | USA | 5.41 | 15% | 15.5 |
| 3 | India | 2.65 | 7% | 1.8 |
| 4 | Russia | 1.71 | 5% | 12.0 |
| 5 | Japan | 1.16 | 3% | 8.9 |
| 6 | Germany | 0.75 | 2% | 8.8 |
| 7 | Iran | 0.72 | 2% | 8.3 |
| 8 | South Korea | 0.72 | 2% | 12.1 |
| 9 | Saudi Arabia | 0.72 | 2% | 17.4 |
| 10 | Indonesia | 0.72 | 2% | 2.2 |
| 11 | Canada | 0.56 | 2% | 15.1 |
| 15 | Turkey | 0.42 | 1% | 4.7 |
| 17 | United Kingdom | 0.37 | 1% | 5.8 |
| 19 | France | 0.33 | 1% | 4.6 |
| 20 | Italy | 0.33 | 1% | 5.3 |

Source: Earth System Science Data, https://earth-system-science-data.net

World Bank Open Data, https://data.worldbank.org/topic/climate-change

# Regulation of climate risk

## UN

Paris Agreement: where we are?

- 194 states have signed the Agreement
- They represent about 80% of GHG emissions
- USA, Iran and Turkey have not signed the Agreement

# Regulation of climate risk
## UN


Figure 11: Paris Agreement assessments of aviation and shipping

Source: Climate Action Tracker (CAT), https://climateactiontracker.org

# Regulation of climate risk

## Coalitions

- **The Coalition of Finance Ministers for Climate Action**

  `www.financeministersforclimate.org`

  - Commitment to implement fully the Paris Agreement
  - Santiago Action Plan
  - Helsinki principles (1. align, 2. share, 3. promote, 4. mainstream, 5. mobilize, 6. engage)

# Regulation of climate risk

## Coalitions

- **One Planet Summit**

  www.oneplanetsummit.fr

- **One Planet Sovereign Wealth Funds (OPSWF)**
  - Funding members: Abu Dhabi Investment Authority (ADIA), Kuwait Investment Authority (KIA), NZ Superannuation Fund (NZSF), Public Invesment Fund (PIF), Qatar Investment Authority (QIA), NBIM
  - New members: Bpifrance, CDP Equity, COFIDES, FONSIS, ISIF, KIC, Mubadala IC, NIIF, NIC NBK
- **One Planet Asset Managers**
  - Funding members: Amundi AM, BlackRock, BNP PAM, GSAM, HSBC Global AM, Natixis IM, Northern Trust AM, SSGA
  - New members: AXA IM, Invesco, Legal & General IM, Morgan Stanley IM, PIMCO UBS AM
- **One Planet Private Equity Funds**
  - Members: Ardian, Carlyle Group, Global Infrastructure Partners, Macquarie Infrastructure and Real Assets (MIRA), SoftBank IA

# Regulation of climate risk
## Countries

### The example of France

- August 2015: French Energy Transition for Green Growth Law (or Energy Transition Law)
- Roadmap to mitigate climate change and diversify the energy mix

Other examples: Germany (2021 Renewable Energy Act), UK (2013 Energy Act), The Netherlands (2019 Climate Change Mitigation Act), etc.

# Regulation of climate risk

## Countries

### Article 173 of the French Energy Transition Law

- The annual report of listed companies must include:
  - Financial risks related to the effects of climate change
  - The measures adopted by the company to reduce them
  - The consequences of climate change on the company's activities
- New requirements for investors:
  - Disclosure of climate (and ESG) criteria into investment decision making process
  - Disclosure of the contribution to the energy transition and the global warming limitation international objective
  - Reporting on climate change-related risks (including both physical risks and transition risks), and GHG emissions of assets
- Banks and credit providers shall conduct climate stress testing

# Regulation of climate risk

## Carbon pricing

- Polluter pays principle
  - A carbon price is a cost applied to carbon pollution to encourage polluters to reduce the amount of GHG they emit into the atmosphere
  - Negative externality
- Two instruments of carbon pricing
  1. **Carbon tax**
  2. **Cap-and-trade** (CAT) or **emissions trading scheme** (ETS)
- Some examples
  1. EU emissions trading system (2005) — `https://ec.europa.eu/clima/policies/ets_en`
  2. New Zealand ETS (2008)
  3. Chinese national carbon trading scheme (2017)

# Regulation of climate risk

## Carbon pricing

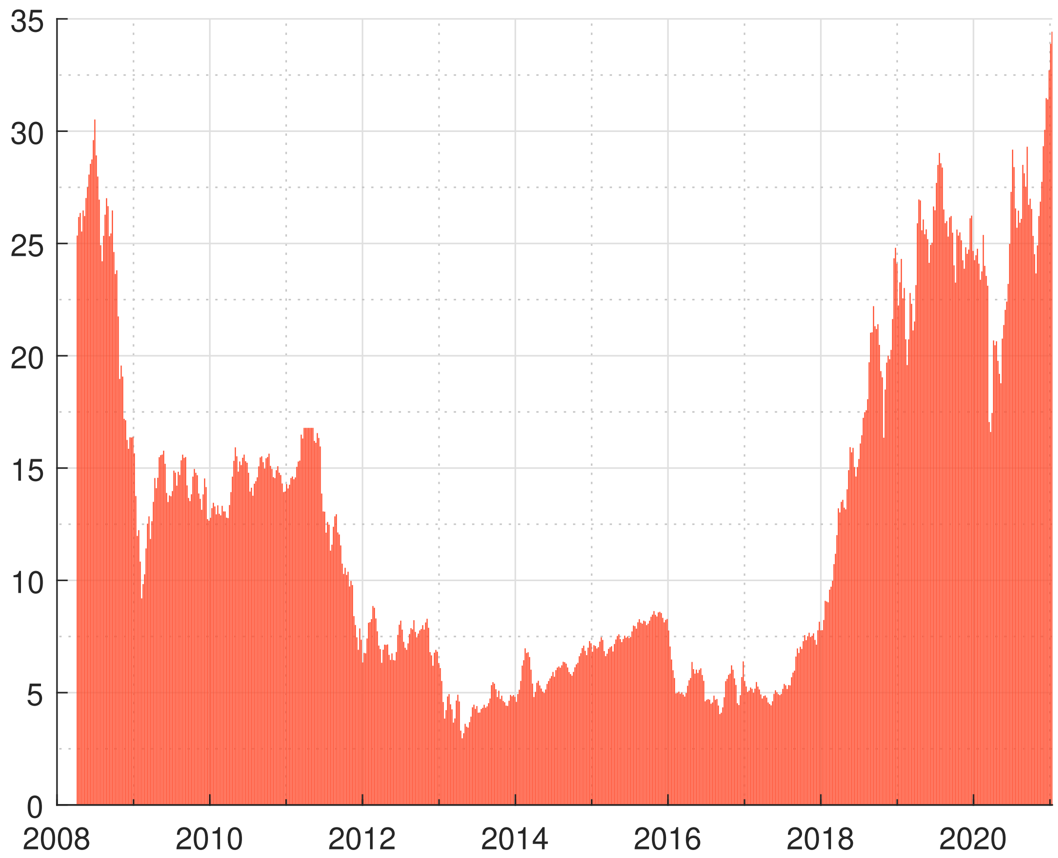



Figure 12: EU ETS carbon price* (in €/t$CO_2$)

(*)The carbon price reaches 34.43 euros a tonne on Monday 11, 2021

# Regulation of climate risk
## Carbon pricing

Table 4: Carbon tax (in $\$/tCO_2$)

| Country | 2018 | 2019 | 2020 | Country | 2018 | 2019 | 2020 |
|---|---|---|---|---|---|---|---|
| Sweden | 139.11 | 126.78 | 133.26 | Latvia | 5.58 | 5.06 | 10.49 |
| Liechtenstein | 100.90 | 96.46 | 105.69 | South Africa | | | 7.38 |
| Switzerland | 100.90 | 96.46 | 104.65 | France | 55.30 | 50.11 | 6.98 |
| Finland | 76.87 | 69.66 | 72.24 | Argentina | | 6.24 | 5.94 |
| Norway | 64.29 | 59.22 | 57.14 | Chile | 5.00 | 5.00 | 5.00 |
| Ireland | 24.80 | 22.47 | 30.30 | Colombia | 5.67 | 5.17 | 4.45 |
| Iceland | 35.71 | 31.34 | 30.01 | Singapore | | 3.69 | 3.66 |
| Denmark | 28.82 | 26.39 | 27.70 | Mexico | 3.01 | 2.99 | 2.79 |
| Portugal | 8.49 | 14.31 | 27.52 | Japan | 2.74 | 2.60 | 2.76 |
| United Kingdom | 25.46 | 23.59 | 23.23 | Estonia | 2.48 | 2.25 | 2.33 |
| Slovenia | 21.45 | 19.44 | 20.16 | Ukraine | 0.02 | 0.37 | 0.35 |
| Spain | 24.80 | 16.85 | 17.48 | Poland | 0.09 | 0.08 | 0.08 |

Source: World Bank Carbon Pricing Dashboard, `https://carbonpricingdashboard.worldbank.org`

# Regulation of climate risk

## Stranded assets

- Stranded Assets are assets that have suffered from unanticipated or premature write-downs, devaluations or conversion to liabilities
- For example, a $2^{\circ}\mathrm{C}$ alignment implies to keep a large proportion of existing fossil fuel reserves in the ground (30% of oil reserves, 50% of gas reserves and 80% of coal)
- Risk factors: Regulations, carbon prices, change in demand, social pressure, etc.
- Example of the covid-19 crisis $\Rightarrow$ air travel

# Regulation of climate risk

## Financial regulation

- Financial Stability Board (FSB)
- European Central Bank (ECB)
- The French Prudential Supervision and Resolution Authority (ACPR)
- The Prudential Regulation Authority (PRA)
- Network for Greening the Financial System (NGFS)
- Etc.

# Regulation of climate risk

## Financial regulation

Bolton, P., Despres, M., Pereira Da Silva, L.A., Samama, F. and Svartzman, R. (2020), *The Green Swan — Central Banking and Financial Stability in the Age of Climate Change*, BIS Publication, https://www.bis.org/publ/othp31.htm

# Regulation of climate risk

## Financial regulation

### Task Force on Climate-related Financial Disclosures (TCFD)

- Established by the FSB in 2015 to develop a set of voluntary, consistent disclosure recommendations for use by companies in providing information to investors, lenders and insurance underwriters about their climate-related financial risks
- Website: `www.fsb-tcfd.org`
- Chairman: Michael R. Bloomberg (founder of Bloomberg L.P.)
- 31 members
- June 2017: Publication of the "*Recommendations of the Task Force on Climate-related Financial Disclosures*"
- October 2020: Publication of the 2020 "*Status Report: Task Force on Climate-related Financial Disclosures*"

# Regulation of climate risk

## Financial regulation

| Recommendation | ID | Recommended Disclosure |
|---|---|---|
| Governance | 1 | Board oversight |
| | 2 | Management's role |
| Strategy | 3 | Risks and opportunities |
| | 4 | Impact on organization |
| | 5 | Resilience of strategy |
| Risk management | 6 | Risk ID and assessment processes |
| | 7 | Risk management processes |
| | 8 | Integration into overall risk management |
| Metrics and targets | 9 | Climate-related metrics |
| | 10 | Scope 1, 2, 3 GHG emissions |
| | 11 | Climate-related targets |

Table 5: The 11 recommended disclosures (TCFD, 2017)

# Regulation of climate risk

## Financial regulation

Some key findings of the 2020 Status Report (TCFD, 2020):

- Disclosure of climate-related financial information has increased since 2017, but continuing progress is needed
- Average level of disclosure across the Task Force's 11 recommended disclosures was 40% for energy companies and 30% for materials and buildings companies
- Asset manager and asset owner reporting to their clients and beneficiaries, respectively, is likely insufficient

# Climate stress testing

- ACPR (2020): Climate Risk Analysis and Supervision[3]
- Bank of England (2021): Climate Biennial Exploratory Scenario (June 2021)

Top-down approach $\neq$ bottom-up approach

Stress of risk-weighted asset: Bouchet and Le Guenedal (2020).

[3] https://acpr.banque-france.fr/en/scenarios-and-main-assumptions-acpr-pilot-climate-exercise

# Climate capital requirements

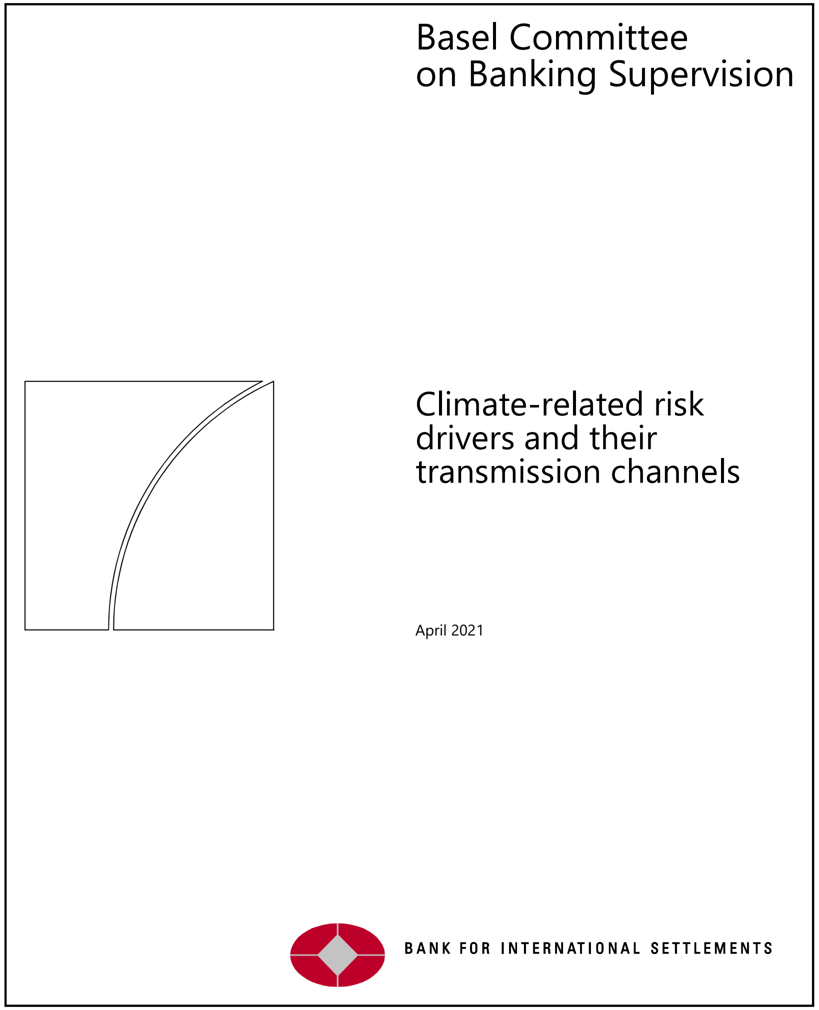
## Green supporting factor

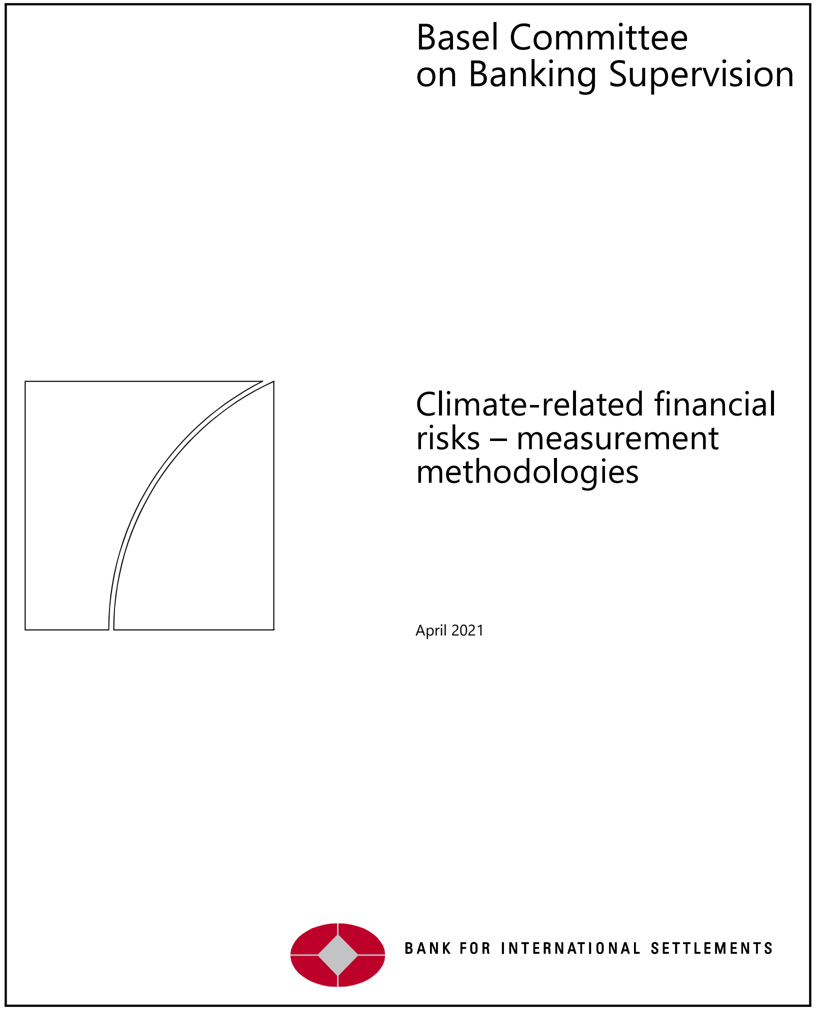
- Risk weights may depend on the green/brown nature of the credit
- Green loans
- Green supporting factor $\neq$ Brown penalising factor

Similar idea: Green Quantitative Easing (GQE)

# Climate capital requirements

Figure 13: In April 2021, Basel Committee publishes two reports on climate risk



# Climate risk modeling

**Remark**

In what follows, we use the survey and the simulations of Le Guenedal (2019)

# Climate risk modeling
## The Solow growth model

### The model

- Production function:

$$Y(t) = F(K(t), A(t) L(t))$$

  where $K(t)$ is the capital, $L(t)$ is the labor and $A(t)$ is the knowledge factor

- Law of motion for the capital per unit of effective labor $k(t) = K(t) / (A(t) L(t))$:

$$\frac{\mathrm{d}k(t)}{\mathrm{d}t} = s f(k(t)) - (g_L + g_A + \delta_K) k(t)$$

  where $s$ is the saving rate, $\delta_K$ is the depreciation rate of capital and $g_A$ and $g_L$ are the productivity and labor growth rates

# Climate risk modeling

## The golden rule

### Golden rule with the Cobb-Douglas production and Hicks neutrality

The equilibrium to respect the '*fairness*' between generations is:

$$k^{\star} = \left( \frac{s}{g_L + g_A + \delta_K} \right)^{\dfrac{1}{1-\alpha}}$$

"*Each generation in a boundless golden age of natural growth will prefer the same investment ratio, which is to say the same natural growth path*" (Phelps, 1961, page 640).

"*By a golden age I shall mean a dynamic equilibrium in which output and capital grow exponentially at the same rate so that the capital-output ratio is stationary over time*" (Phelps, 1961, page 639).

# Climate risk modeling

## Golden rule and climate risk

**What is economic growth and what is the balanced growth path?**

- There is a saving rate that maximizes consumption over time and between generations ("**the fair rate to preserve future generations**")
- Economic growth corresponds to the exponential growth of capital and output to answer the needs of the growing population
- Introducing human and natural capitals add constraints and therefore **reduce growth**!

Economic growth $\Rightarrow \begin{cases} \text{productivity} \nearrow \text{ and labor } \nearrow \\ \text{maximization of } \textbf{consumption-based utility} \text{ function} \end{cases}$

# Climate risk modeling

## Extension to natural capital

What are the effects of environmental constraints on growth?

**Introducing a decreasing natural capital (Romer, 2006)**

The balanced growth path $g_Y^\star$ is equal to:

$$g_Y^\star = g_L + g_A - \frac{g_L + g_A + \delta_{N_c}}{1 - \alpha} \vartheta$$

where $\delta_{N_c}$ is the depreciation rate of natural capital and $\vartheta$ is the elasticity of output with respect to (normalized) natural capital $N_c(t)$

"*The static-equilibrium type of economic theory which is now so well developed is plainly inadequate for an industry in which the indefinite maintenance of a steady rate of production is a physical impossibility, and which is therefore bound to decline*" (Hotteling, 1931, page 138-139)

**Accounting for environment... changes the definition of economic growth**

# Climate risk modeling

## Inter-temporal utility functions

### Preferences modeling (Ramsey model)

- $\rho$ is the discount rate (time preference)
- $c(t)$ is the consumption per capita and $u$ is the CRRA utility function:

$$u(c(t)) = \begin{cases} \dfrac{1}{1-\theta} c(t)^{1-\theta} & \text{if } \theta > 0, \quad \theta \neq 1 \\ \ln c(t) & \text{if } \theta = 1 \end{cases}$$

  where $\theta$ is the risk aversion parameter

- Maximization of the welfare function:

$$\int_t^\infty e^{-\rho t} u(c(t)) \, \mathrm{d}t$$

# Climate risk modeling
## The discounting issue

Does the golden rule of saving rates hold in a Keynesian approach with discounted maximization of consumption?

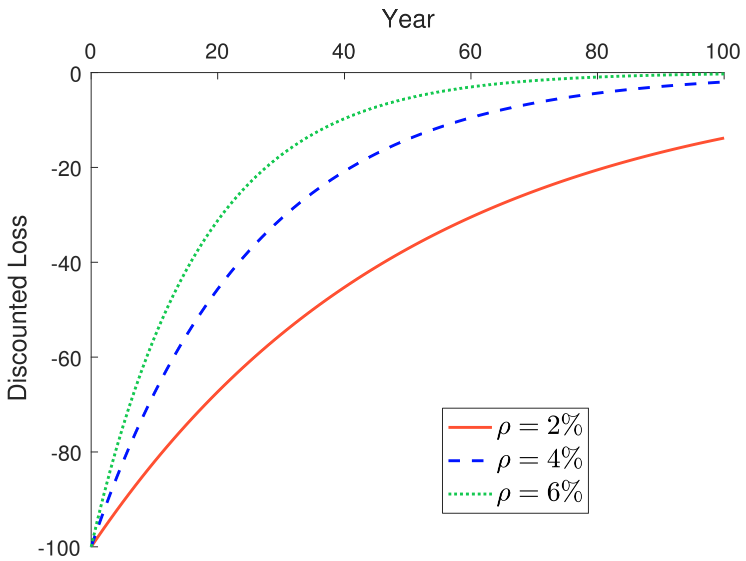



Figure 14: Discounted value of \$100 loss

- *"There is still time to avoid the worst impacts of climate change, if we take strong action now"* (Stern, 2007)
- *"I got it wrong on climate change – it's far, far worse"* (Stern, 2013)

The value of a loss in 100 years almost disappears... while it is only the next generation!

# Climate risk modeling

## Does consumption maximization make sense?

### How many planets do we need?

To achieve the current levels of consumption for the world population, we need:

- US: 5 planets
- France: 3 planets
- India: 0.6 planet

Source: Global Footprint Network, http://www.footprintcalculator.org

# Climate risk modeling

## Fairness between generations

**Keynes**

*"In the long run, we are all dead"*

John Maynard Keynes[a], *A Tract on Monetary Reform*, 1923.

[a] *"Men will not always die quietly"*, *The Economic Consequences of the Peace*, 1919.

**Carney**

*"The Tragedy of the Horizon"*

Mark Carney, Chairman of the Financial Stability Board, 2015

⇒ Back to the Golden Rule and the Fable for Growthmen...

# Integrated assessment model (IAM)

## Definition

### Main categories

- **Optimization models**
  The inputs of these models are parameters and assumptions about the structure of the relationships between variables. The outputs provided by optimization process are scenarios depending on a set of constraints
- **Evaluation models**
  Based on exogenous scenarios, the outputs provide results from partial equilibriums between variables

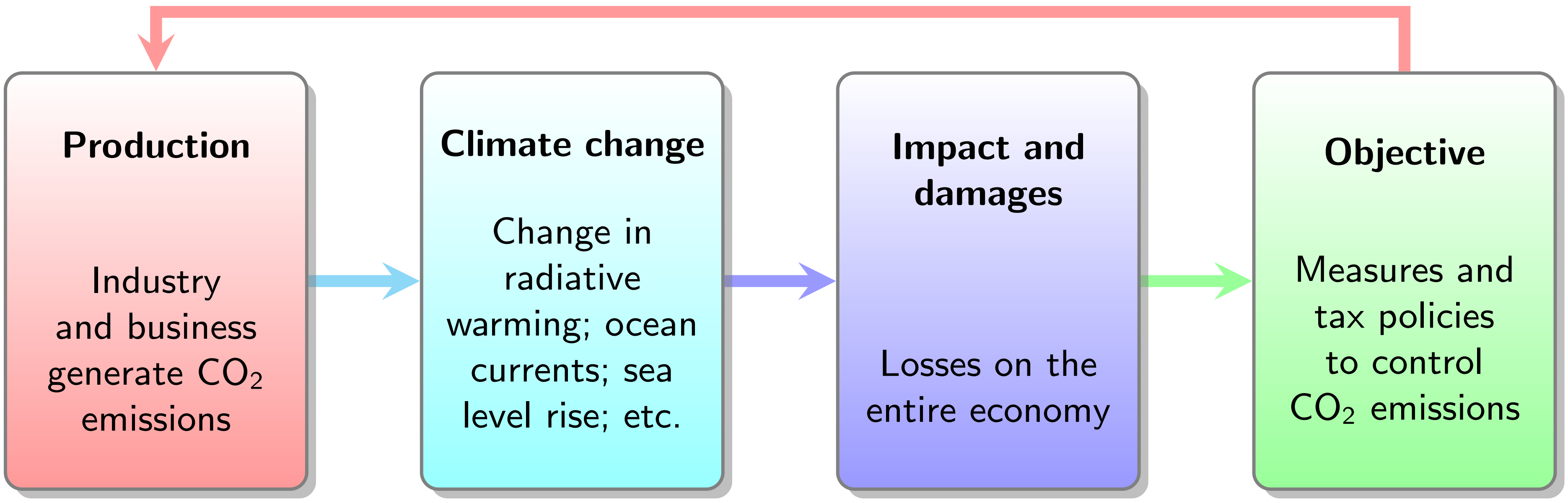
### Three main components of IAMs

1. Economic growth relationships
2. Dynamics of climate emissions
3. Objective function

# Integrated assessment model (IAM)

## Modeling framework

Figure 15: Economic models of climate risk



# Integrated assessment model (IAM)

## Modeling framework

1. Economic module
   1. Production function $\Longrightarrow$ GDP
   2. Impact of the climate risk on GDP (damage losses, mitigation and adaptation costs)
   3. The climate loss function depends on the temperature
2. Climate module
   1. Dynamics of GHG emissions
   2. Modeling of Atmospheric and lower ocean temperatures
3. Optimal control problem
   1. Maximization of the utility function
   2. We can test many variants

# Integrated assessment model (IAM)

## Modeling framework

The most famous IAM is the **Dynamic Integrated model of Climate and the Economy** (or DICE) developed by Nordhaus[4] (1993)

The RICE model (Regional Integrated Climate-Economy model) is a variant of the DICE model

[4] 2018 Nobel Laureate

# Integrated assessment model (IAM)

## Production and output

- The **gross output** is equal to:

$$Y(t) = A_{\mathrm{TFP}}(t) K(t)^{\alpha} L(t)^{1-\alpha}$$

where:

$$\begin{cases} A_{\mathrm{TFP}}(t) = (1 + g_A(t)) A_{\mathrm{TFP}}(t-1) \\ K(t) = (1 - \delta_K) K(t-1) + I(t) \\ L(t) = (1 + g_L(t)) L(t-1) \end{cases}$$

- Climate change impacts the **net output**:

$$Q(t) = \Omega_{\mathrm{Climate}}(t) Y(t)$$

- We also have $Q(t) = C(t) + I(t)$ and $C(t) = (1 - s(t)) Q(t)$

# Integrated assessment model (IAM)

## The loss (or damage) function

- The loss function is given by:

$$\Omega_{\mathrm{Climate}}(t) = \Omega_D \cdot \Omega_\Lambda = \frac{1}{1 + D(t)} \cdot (1 - \Lambda(t))$$

where $D(t)$ and $\Lambda(t)$ measure climate damages[5] and abatement costs[6]

- Climate damages are assumed to be quadratic:

$$D(t) = a_1 \mathcal{T}_{\mathrm{AT}}(t) + a_2 \mathcal{T}_{\mathrm{AT}}(t)^2$$

where $\mathcal{T}_{AT}(t)$ is the atmospheric temperature, while abatement costs depend on the control rate $\mu(t)$:

$$\Lambda(t) = b_1 \mu(t)^{b_2}$$

[5] The climate damage coefficient $\Omega_D(t) = (1 + D(t))^{-1}$ represents the fraction of GDP loss because of the temperature increase

[6] It includes costs of reduction of greenhouse gases emission, abatement and mitigation costs

# Integrated assessment model (IAM)

## GHG emissions, concentrations and radiative forcing

- The total emission of green house gases $\mathcal{E}(t)$ is given by:

$$\mathcal{E}(t) = (1 - \mu(t))\,\sigma(t)\,Y(t) + \mathcal{E}_{\mathrm{Land}}(t)$$

  where mitigation policies are translated by the control rate $\mu(t)$, $\mathcal{E}_{\mathrm{Land}}(t)$ represents exogenous land-use emissions and $\sigma(t)$ is the uncontrolled ratio of green house gases emissions to output

- The evolution of the GHG concentration $\mathcal{C} = (\mathcal{C}_{\mathrm{AT}}, \mathcal{C}_{\mathrm{UP}}, \mathcal{C}_{\mathrm{LO}})$ is given by:

$$\mathcal{C}(t) = \Phi_{\mathcal{C},\Delta}\mathcal{C}(t-1) + B_{\mathcal{C},\Delta}\mathcal{E}(t)$$

- The increase of radiative forcing $\mathcal{F}_{\mathrm{RAD}}(t)$ depends on the GHG concentration in the atmosphere:

$$\mathcal{F}_{\mathrm{RAD}}(t) = \eta \ln_2\left(\frac{\mathcal{C}_{\mathrm{AT}}(t)}{\mathcal{C}_{\mathrm{AT}}(1750)}\right) + \mathcal{F}_{\mathrm{EX}}(t)$$

# Integrated assessment model (IAM)

## Temperatures

Atmospheric and lower ocean temperatures are given by:

$$\begin{aligned} C_{\mathrm{AT}} \frac{\mathrm{d}\mathcal{T}_{\mathrm{AT}}(t)}{\mathrm{d}t} &= \mathcal{F}_{\mathrm{RAD}}(t) - \lambda \mathcal{T}_{\mathrm{AT}}(t) - \gamma(\mathcal{T}_{\mathrm{LO}}(t) - \mathcal{T}_{\mathrm{AT}}(t)) \\ C_{\mathrm{LO}} \frac{\mathrm{d}\mathcal{T}_{\mathrm{LO}}(t)}{\mathrm{d}t} &= \gamma(\mathcal{T}_{\mathrm{LO}}(t) - \mathcal{T}_{\mathrm{AT}}(t)) \end{aligned}$$

where $\gamma$ is the heat exchange coefficient and $\lambda$ is the climate feedback parameter.

# Integrated assessment model (IAM)

## The optimal control problem

### Simplified version of the DICE model (Nordhaus, 1993)

$$\{\mu^\star(t), s^\star(t)\} = \arg\max \sum_{t=0}^{T} \frac{u(c(t), L(t))}{(1+\rho)^t}$$

$$\text{s.t.} \quad \begin{cases} Y(t) = A_{\mathrm{TFP}}(t) K(t)^\alpha L(t)^{1-\alpha} \\ A_{\mathrm{TFP}}(t) = (1 + g_A(t)) A_{\mathrm{TFP}}(t-1) \\ K(t) = (1-\delta_K) K(t-1) + I(t) \\ L(t) = (1 + g_L(t)) L(t-1) \\ Q(t) = \Omega_{\mathrm{C\,lim\,ate}}(t) Y(t) \\ C(t) = (1 - s(t)) Q(t) \\ \mathcal{E}(t) = (1 - \mu(t)) \sigma(t) Y(t) + \mathcal{E}_{\mathrm{Land}}(t) \\ \mathcal{C}(t) = \Phi_{\mathcal{C},\Delta} \mathcal{C}(t-1) + B_{\mathcal{C},\Delta} \mathcal{E}(t) \\ \mathcal{F}_{\mathrm{RAD}}(t) = \eta \log_2\left(\frac{\mathcal{C}_{\mathrm{AT}}(t)}{\mathcal{C}_{\mathrm{AT}}(1750)}\right) + \mathcal{F}_{\mathrm{EX}}(t) \\ \mathcal{T}(t) = \Phi_{\mathcal{T},\Delta} \mathcal{T}(t-1) + B_{\mathcal{T},\Delta} \mathcal{F}_{\mathrm{RAD}}(t) \end{cases}$$

# Integrated assessment model (IAM)

## Scenario analysis

The process of building scenarios is the same in every model

1. Choice of the structure
   - Optimization or evaluation?
   - Optimization function?
   - Complexity or simplicity?
2. Calibration
   - Choice for the discount rate (Nordhaus vs Stern)
   - Calibration of energy prices and substitution (etc.)
3. Applications
   - Compare baseline scenario of the different models
   - Compute the 2°C scenario, the optimal welfare scenario, etc.

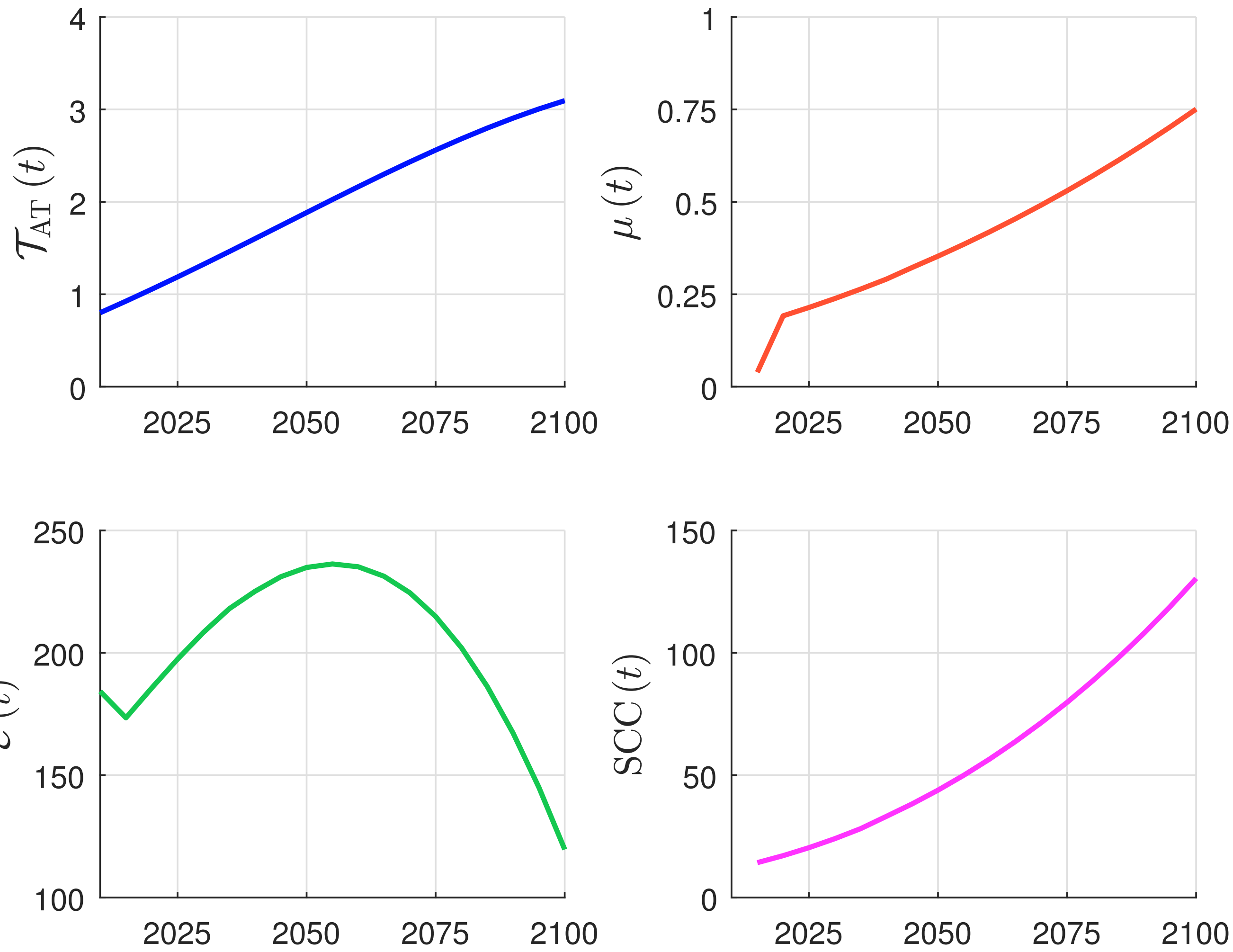
# Integrated assessment model (IAM)

## Important variables

- $\mathcal{T}_{\mathrm{AT}}(t)$ — Atmospheric temperature
- $\mu(t)$ — Control rate (mitigation policies)
- $\mathcal{E}(t)$ — Total emissions of GHG
- $\mathrm{SCC}(t)$ — Social cost of carbon

# Integrated assessment model (IAM)

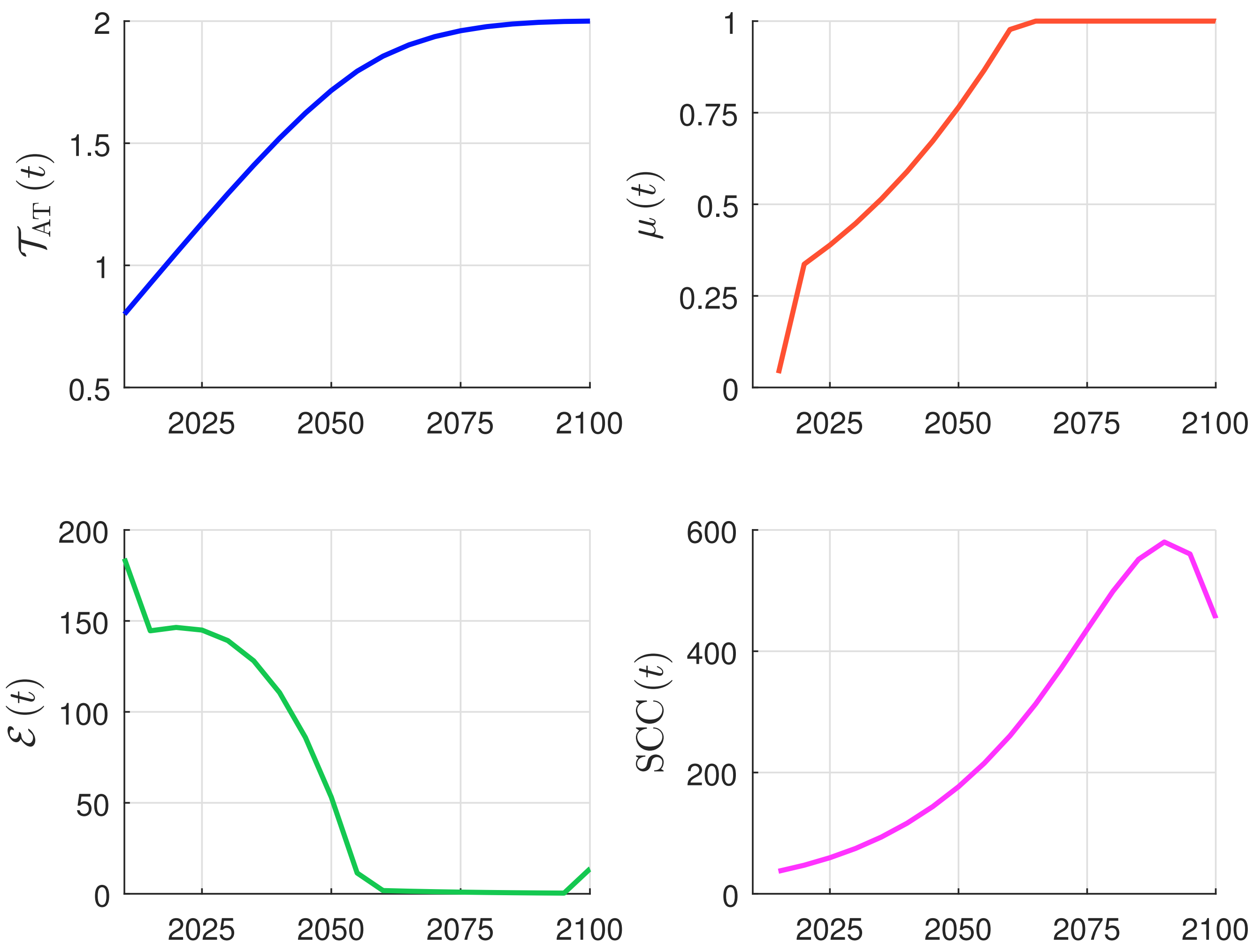
## 2013 DICE optimal welfare scenario




Source: Le Guenedal (2019)

# Integrated assessment model (IAM)

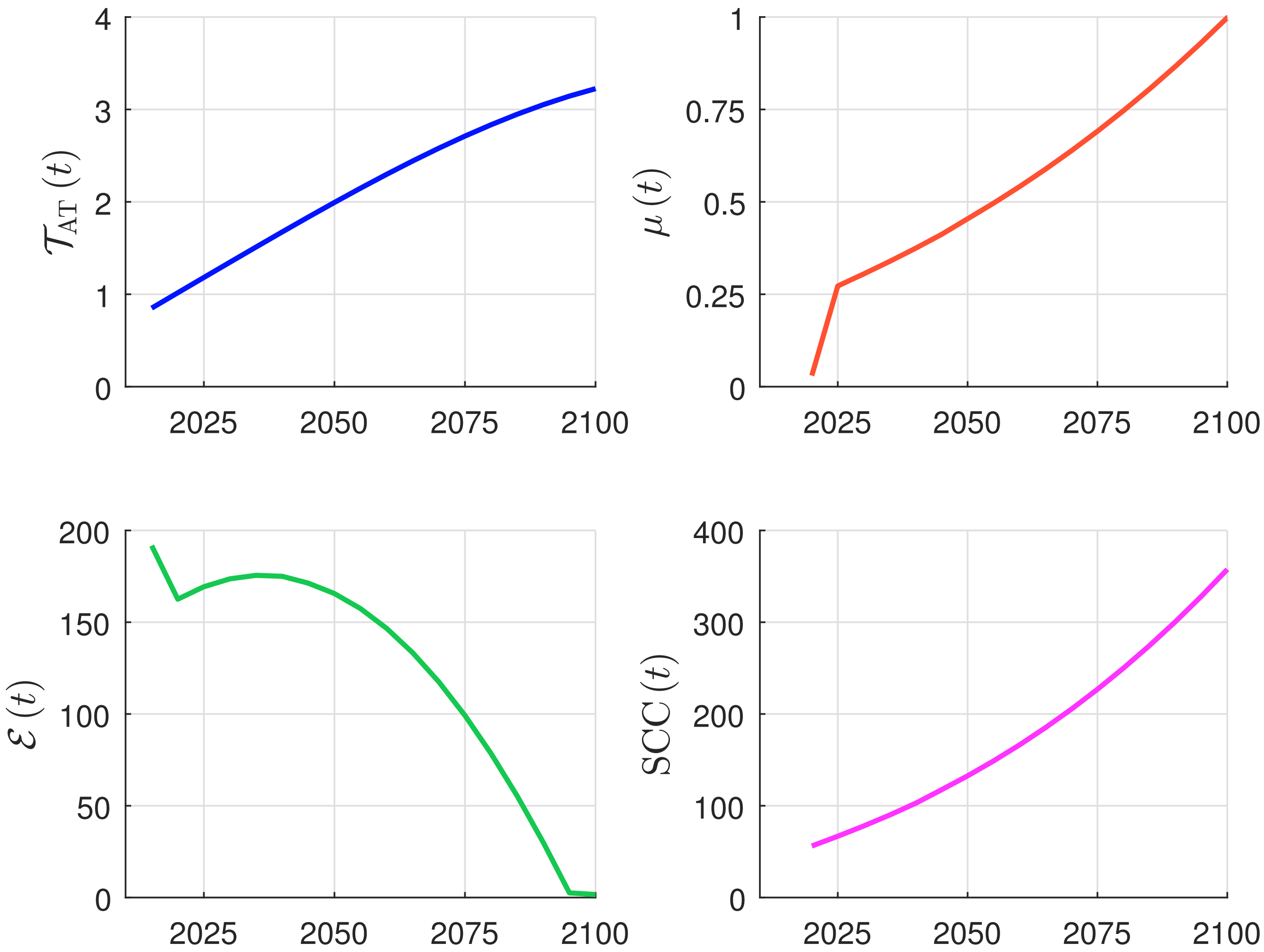
## 2013 DICE 2°C scenario




Source: Le Guenedal (2019)

# Integrated assessment model (IAM)

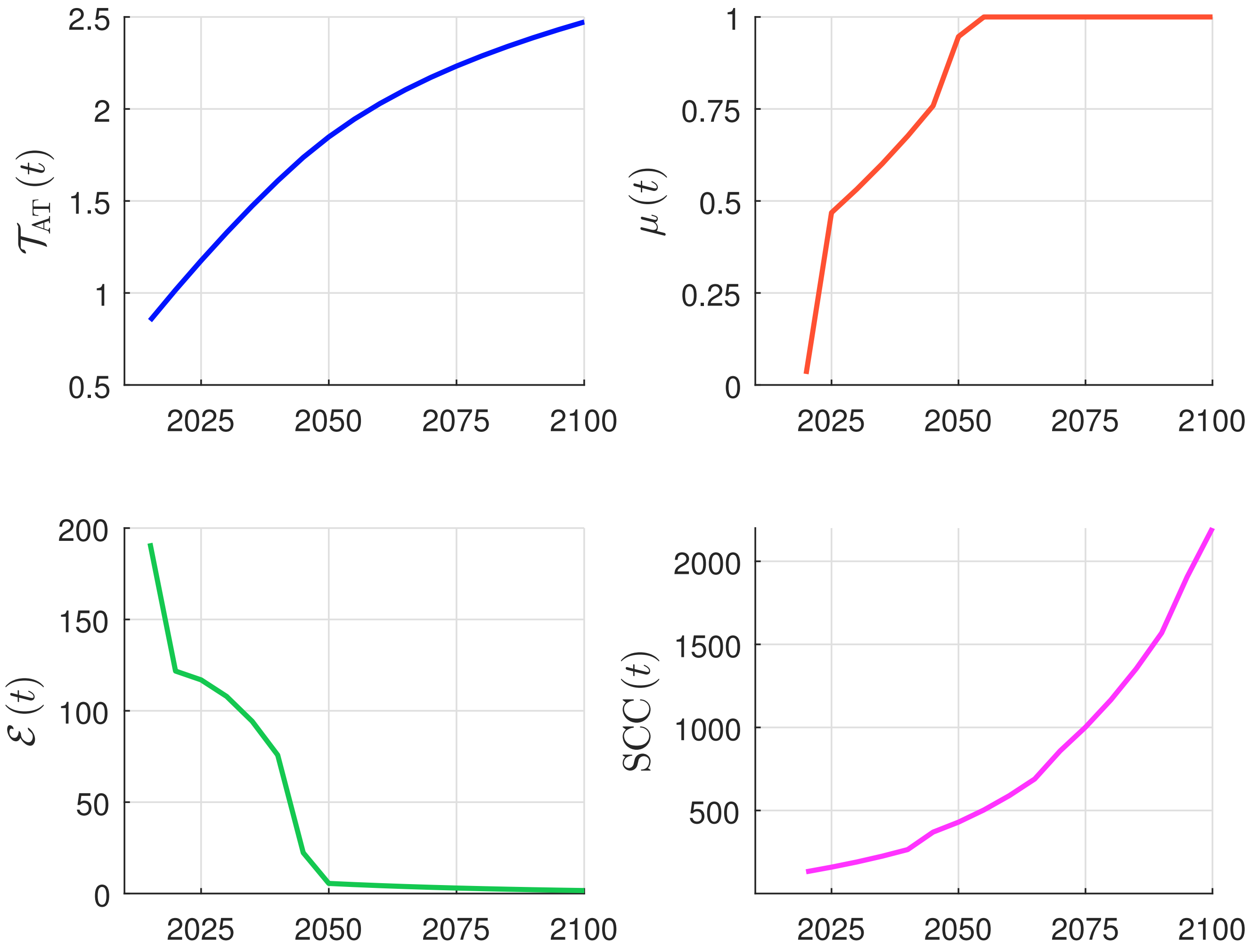
## 2016 DICE optimal welfare scenario




Source: Le Guenedal (2019)

# Integrated assessment model (IAM)

## 2016 DICE 2°C scenario




Source: Le Guenedal (2019)

# Integrated assessment model (IAM)

## The tragedy of the horizon

### Achieving the 2°C scenario

- In 2013, the DICE model suggested to reduce drastically $CO_2$ emissions...
- Since 2016, **the 2°C trajectory is no longer feasible!** (minimum ≈ 2.6°C)
- For many models, we now have:

$$\mathbb{P}\left(\Delta T > 2^{\circ} C\right) > 95\%$$

# Integrated assessment model (IAM)

## Malthusianism and climate risk

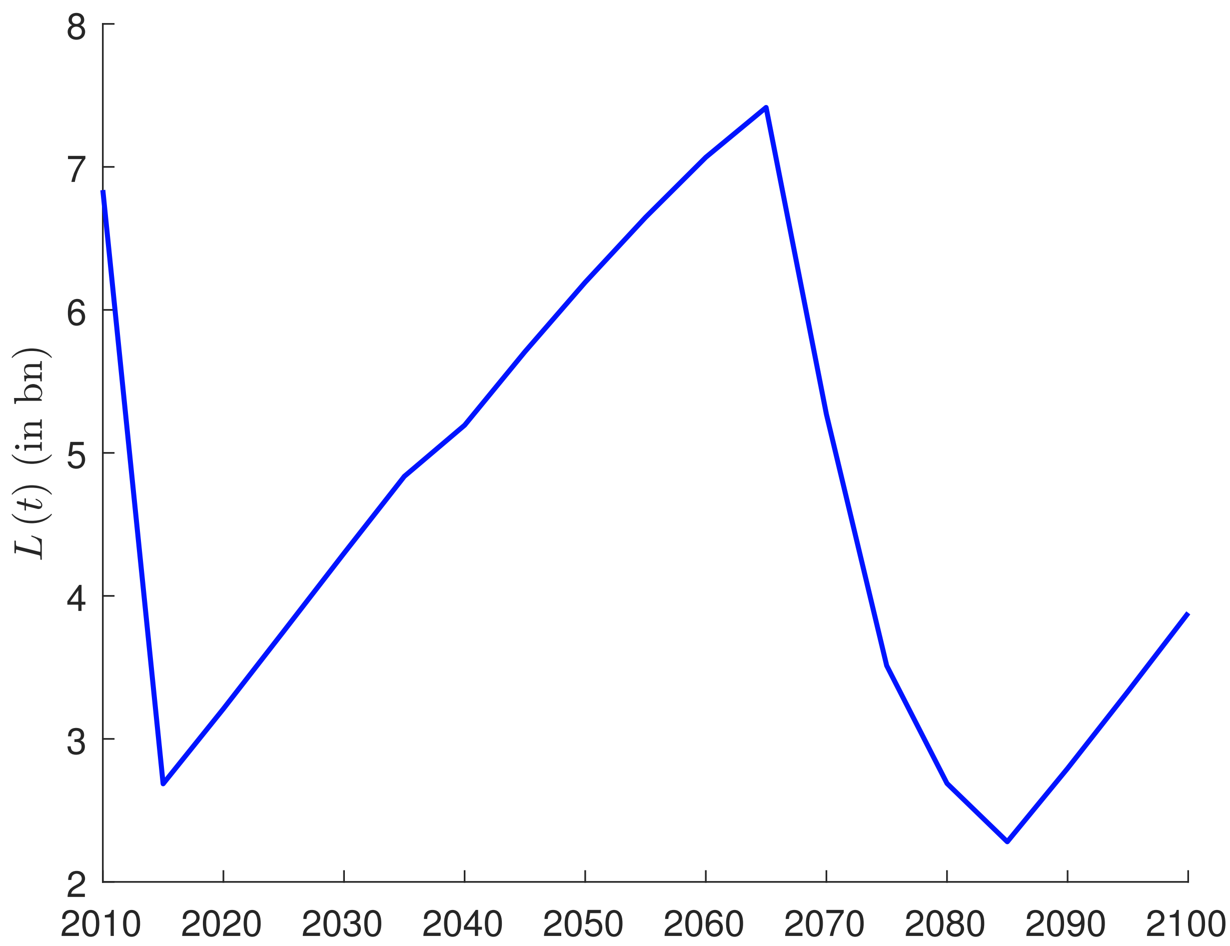



Figure 16: Optimal control on population growth rate (2°C scenario)

# Integrated assessment model (IAM)

## Social cost of carbon (SCC)

*"This concept represents the economic cost caused by an additional ton of carbon dioxide emissions (or more succinctly carbon) or its equivalent. [...] In the language of mathematical programming, the SCC is the shadow price of carbon emissions along a reference path of output, emissions, and climate change" (Nordhaus, 2011).*

### Mathematical definition

We have:

$$\mathrm{SCC}(t) = \frac{\partial W^{\star} / \partial \mathcal{E}(t)}{\partial W^{\star} / \partial C(t)} = \frac{\partial C(t)}{\partial \mathcal{E}(t)}$$

# Integrated assessment model (IAM)

## Debate around the social cost of carbon

We have:

- \$266/t$CO_2$ for Stern (2007)
- \$57/t$CO_2$ for Golosov *et al.* (2014)
- \$31.2/t$CO_2$ for Nordhaus (2018) in the case of optimal welfare
- \$229/t$CO_2$ for Nordhaus (2018) in the case of the 2.5°C scenario
- \$125/t$CO_2$ for Daniel *et al.* (2018)

# Integrated assessment model (IAM)

## Limits of IAMs

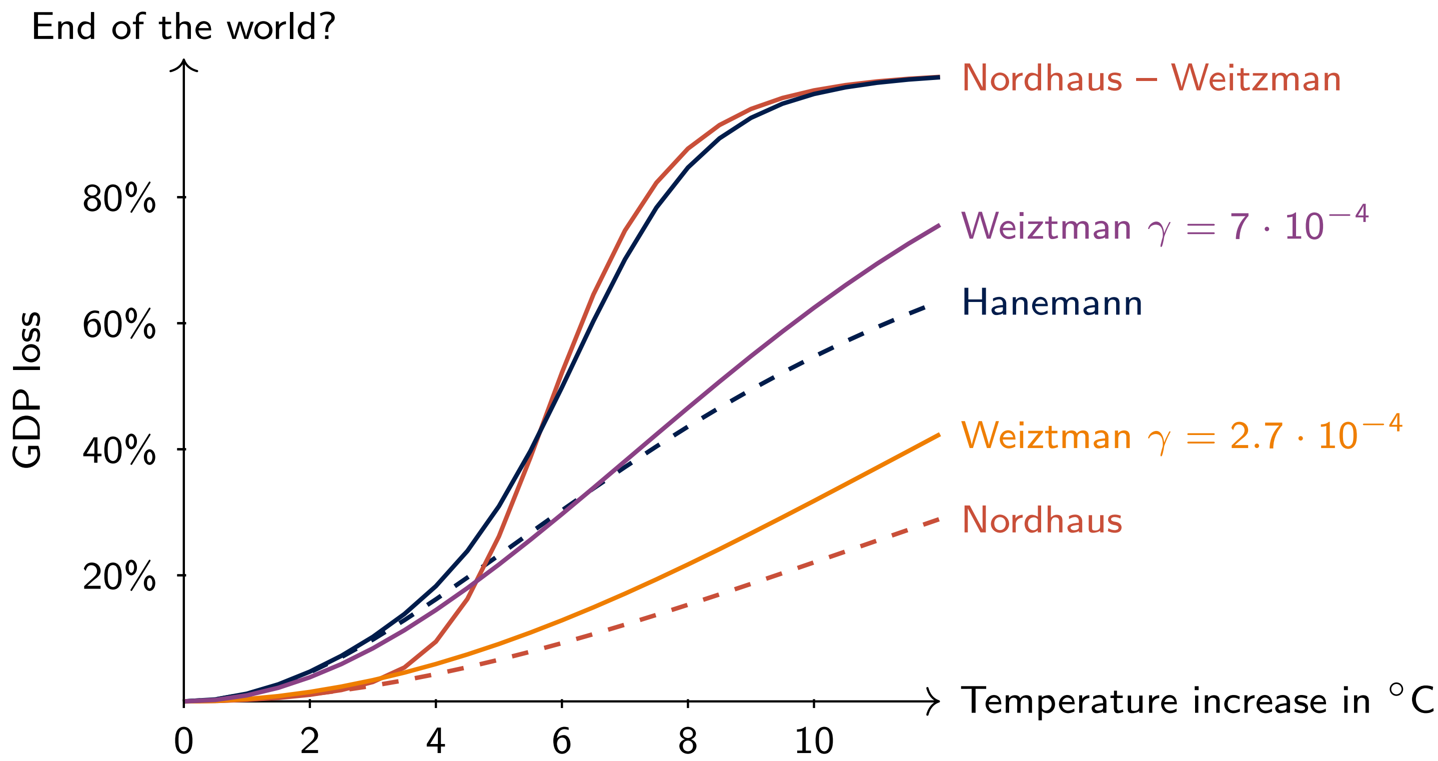



Figure 17: Damage functions

$\Rightarrow$ There is high uncertainty above 2°C and **financial models cannot be based on damage functions**

# Integrated assessment model (IAM)

## Limits of IAMs

- Financial models do not account for portfolio contribution to the technical change (**adaptation/mitigation**)
- The direct exposure to an **optimal tax** (regulation risk) may be approached by using optimization models of policy makers. However, each model leads to a different carbon price...
- Interconnectedness and systemic risks
- First round losses $\neq$ second round losses
- Stranded assets

# Integrated assessment model (IAM)

- AIM ________________________ RCP 6.0
- DICE/RICE
- FUND
- GCAM
- IMACLIM (CIRED)
- IMAGE ________________________ RCP 2.6
- MESSAGE ________________________ RCP 8.5
- MiniCAM ________________________ RCP 4.5
- PAGE
- REMIND
- RESPONSE (CIRED)
- WITCH

# Climate risk and inequalities

**Three types of inequalities**

- Spatial (or regional) inequalities
- Social (or intra-generation) inequalities
- Time (or inter-generation) inequalities

$\Rightarrow$ These issues are highly related to liability risks:

> *"[...] liability risks stemming from parties who have suffered loss from the effects of climate change seeking compensation from those they hold responsible" (Mark Carney, 2018)*

- Regional inequalities $\Rightarrow$ lack of cooperation between countries (e.g., Glasgow COP 26)
- Social inequalities $\Rightarrow$ climate action postponing (e.g., carbon tax in France)

# Regional inequalities

The **R**egional **I**ntegrated model of **C**limate and the **E**conomy (RICE) model is a sub-regional neoclassical climate economy model (Nordhaus and Yang, 1996)

⇒ Sub-regional problem of welfare:

- Each region of the world has a different utility functions
- The big issue is how the most developed regions can finance the transition to a low-carbon economy of the less developed regions

**Both spacial and time (inter-generation) inequalities**

# Social inequalities

The **N**ested **I**nequalities **C**limate-**E**conomy (NICE) model integrates distributional differences of income (Dennig *et al.*, 2015)

> *"[...] If the distribution of damage is less skewed to high income than the distribution of consumption, then weak or no climate policy will result in sufficiently large damages on the lower economic strata to eventually stop their welfare levels from improving, and instead cause them to decline" (Dennig et al., 2015)*

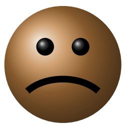
**Both social (intra-generation) and time (inter-generation) inequalities**

# Climate risk measurement

- Climate risk = risk factor for long-term investors, because of its impacts on asset prices
- Managing climate risk in a portfolio first requires to measure it
- We face two dimensions that are highly related: physical risk and transition risk

## Physical risk

- More an operational risk than a business risk?
- Measuring physical risk is a difficult task
- Strong impact on real estate & insurance sectors
- Low impact on stock prices?



## Transition risk

- A business risk
- Measuring transition risk is a difficult task
- Impact on many sectors (energy, materials, industrials, utilities, etc.)
- High impact on stock prices?

# Carbon footprint

- Carbon footprint = generic term used to define the total greenhouse gas (GHG) emissions
- Carbon footprint is measured in carbon dioxide equivalent ($CO_2e$)
- Carbon emissions cannot be compared fairly if the size of the two companies differs (carbon emissions $\Rightarrow$ carbon intensities)

# Carbon emissions

The GHG Protocol corporate standard classifies a company's greenhouse gas emissions in three scopes:

- **Scope 1**: direct GHG emissions from all direct GHG emissions by the company
- **Scope 2**: indirect GHG emissions from the consumption of purchased energy (electricity, heat, steam, etc.)
- **Scope 3**: other indirect GHG emissions (not included in Scope 2) that occur in the value chain of the reporting company, including both upstream and downstream emissions:
    - **Scope 3 upstream**: indirect emissions that come from the supply side (extraction and production of purchased materials and fuels, transport-related activities in vehicles not owned or controlled by the reporting entity, electricity-related activities not covered in Scope 2, outsourced activities, etc.)
    - **Scope 3 downstream**: indirect emissions associated with the product sold by the entity (use of the product, waste disposal, recycling, etc.)

# Carbon emissions

$\mathcal{CE}_1$, $\mathcal{CE}_2$ and $\mathcal{CE}_3$ are expressed in tons of carbon dioxide equivalent or $tCO_2e$

**Remark**

Scopes 1 and 2 are mandatory to report, whereas scope 3 is voluntary (and harder to measure and monitor)

# Carbon emissions

Data on GHG emissions:

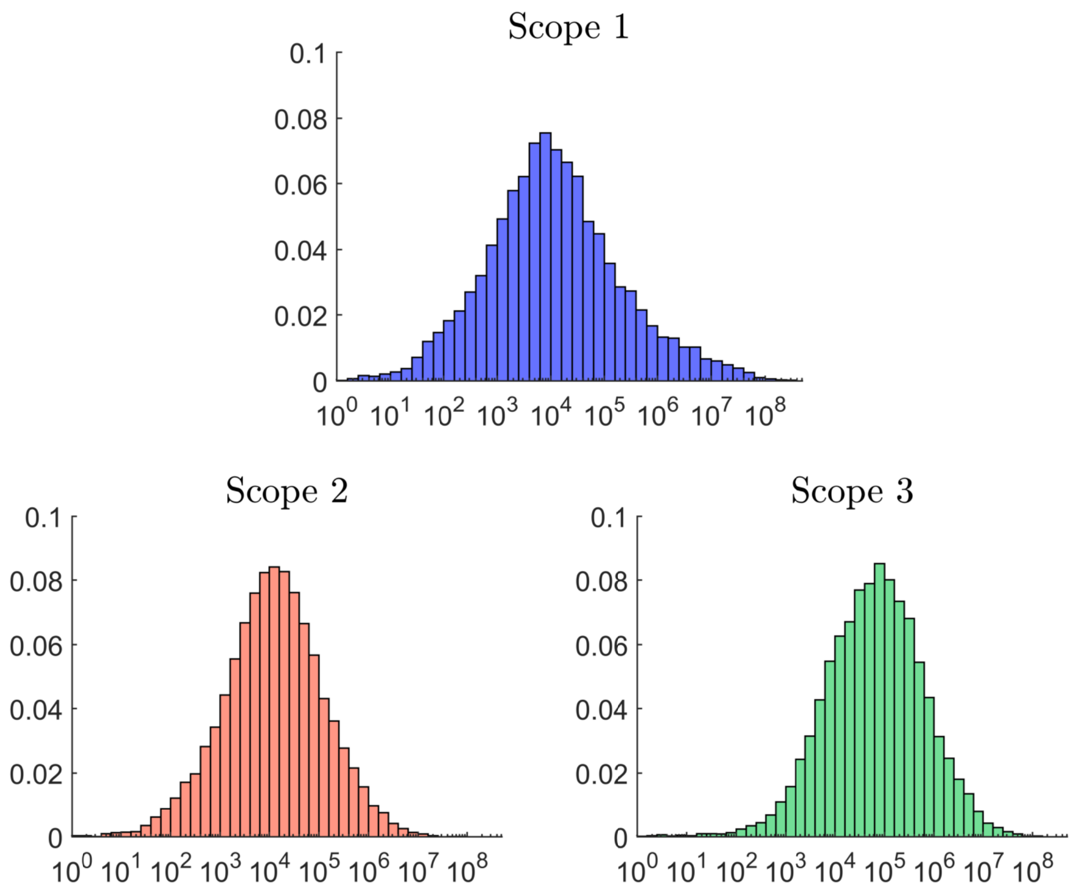
- Countries and regions: World Bank (`data.worldbank.org/topic/climate-change`), Climate Watch Data (`www.climatewatchdata.org/ghg-emissions`), Global Carbon Project (`www.globalcarbonproject.org`), etc.
- Corporates:
  1. CDP (Carbon Disclosure Project) = self-reported values of companies
  2. S&P Trucost data = CDP + estimated values

## S&P Trucost data

- For the year 2019, we have about 15 700 corporations
- $\mathcal{CE}_1 = 15.57$ $GtCO_2e$, $\mathcal{CE}_2 = 2.45$ $GtCO_2e$ and $\mathcal{CE}_3 = 10.17$ $GtCO_2e$
- $\mathcal{CE}_1 + \mathcal{CE}_2 + \mathcal{CE}_3 = 28.2$ $GtCO_2e$ ($\geq 75\%$ of the 36 $GtCO_2e$ global emissions)

# Carbon emissions

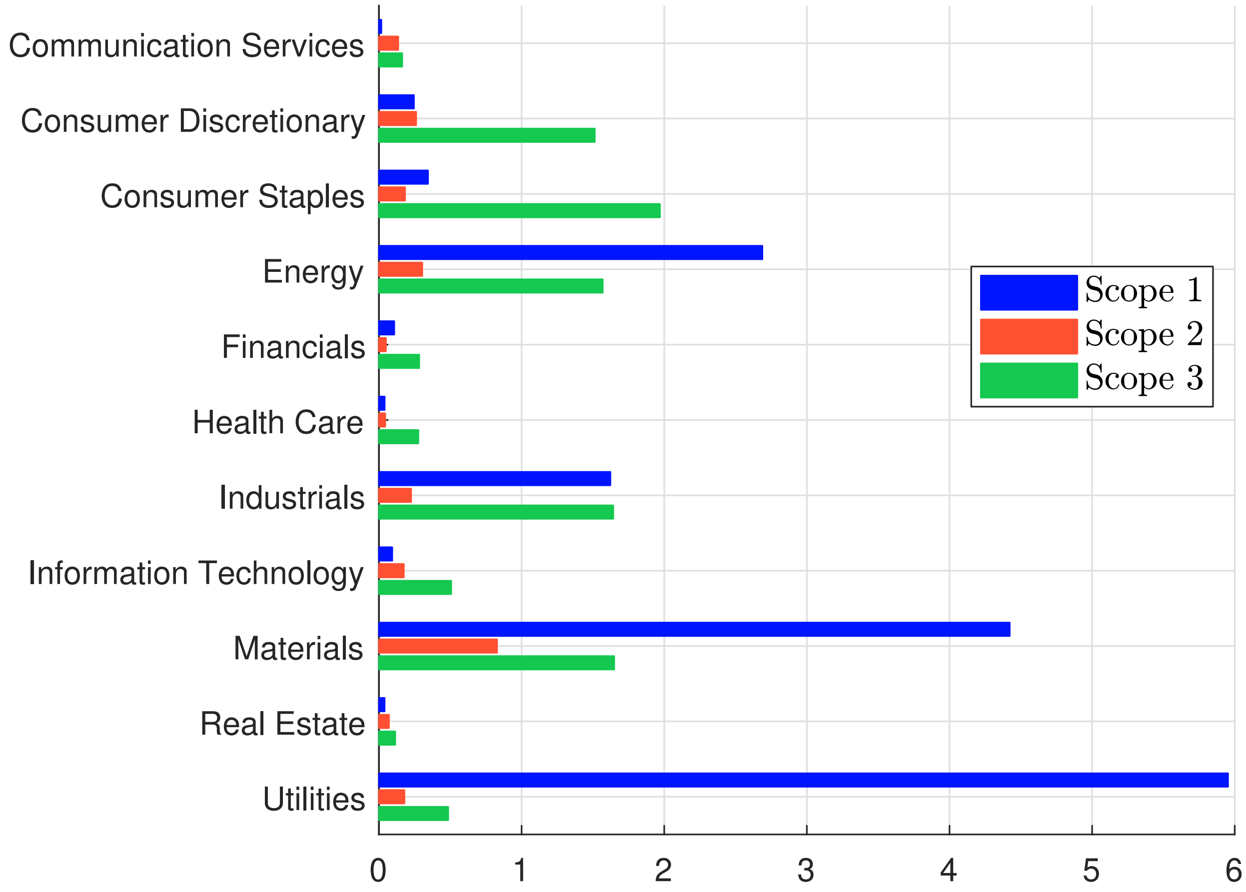
Figure 18: Histogram of carbon emission (log scale, $tCO_2e$)




Source: Trucost reporting year 2019 & Le Guenedal and Roncalli (2022).

# Carbon emissions

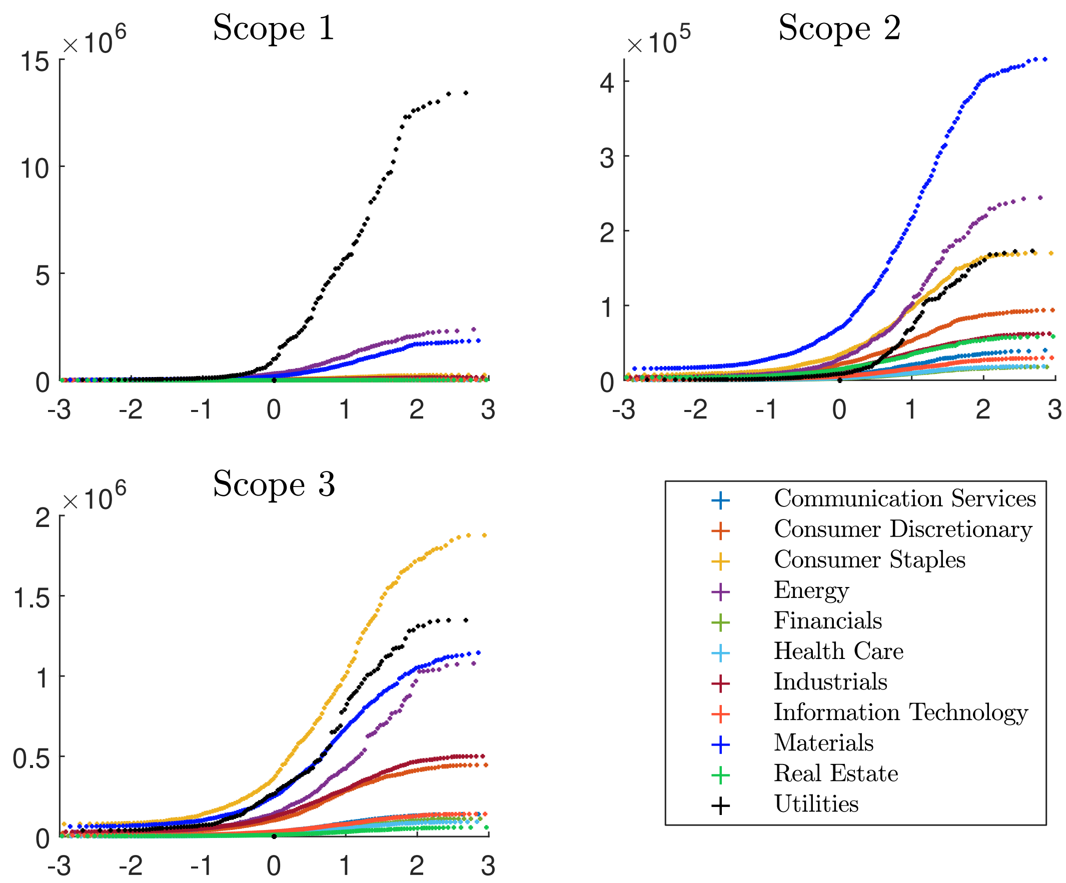
Figure 19: Total absolute scopes per GICS sector in $GtCO_2e$




Source: Trucost reporting year 2019 & Le Guenedal and Roncalli (2022).

# Carbon emissions

Figure 20: QQ-plot of carbon scopes per GICS sector in $MtCO_2e$




Source: Trucost reporting year 2019 & Le Guenedal and Roncalli (2022).

# Carbon emissions

Table 6: Scope 1 + 2 vs. scope 3

| Sector | Breakdown (in %) | | | | | Multiplier |
|---|---|---|---|---|---|---|
| | $\mathcal{SC}_1$ | $\mathcal{SC}_2$ | $\mathcal{SC}_3$ | $\mathcal{SC}_{1+2}$ | $\mathcal{SC}_{1+2+3}$ | $\frac{\mathcal{SC}_3}{\mathcal{SC}_{1+2}}$ |
| Communication Services | 0.11 | 5.52 | 1.60 | 0.84 | 1.12 | 1.07 |
| Consumer Discretionary | 1.57 | 10.64 | 14.88 | 2.81 | 7.16 | 2.99 |
| Consumer Staples | 2.21 | 7.46 | 19.37 | 2.92 | 8.85 | 3.74 |
| Energy | 17.26 | 12.39 | 15.42 | 16.60 | 16.18 | 0.52 |
| Financials | 0.69 | 2.00 | 2.78 | 0.87 | 1.55 | 1.81 |
| Health Care | 0.26 | 1.79 | 2.71 | 0.47 | 1.28 | 3.29 |
| Industrials | 10.42 | 9.20 | 16.15 | 10.25 | 12.38 | 0.89 |
| Information Technology | 0.60 | 7.11 | 4.98 | 1.48 | 2.74 | 1.89 |
| Materials | 28.40 | 33.76 | 16.21 | 29.13 | 24.47 | 0.31 |
| Real Estate | 0.25 | 2.87 | 1.12 | 0.61 | 0.79 | 1.04 |
| Utilities | 38.23 | 7.28 | 4.77 | 34.02 | 23.47 | 0.08 |

Source: Trucost reporting year 2019 & Le Guenedal and Roncalli (2022).

**Considering or not scope 3 emissions gives two different pictures!**

# Carbon intensity

## Definition

The carbon intensity of company $i$ with respect to scope $j$ is a normalization of the carbon emissions:

$$\mathcal{CI}_{i,j} = \frac{\mathcal{CE}_{i,j}}{Y_i}$$

where:

- $\mathcal{CE}_{i,j}$ is the company's absolute scope $j$ emissions
- $Y_i$ is an output indicator measuring its activity

# Carbon intensity

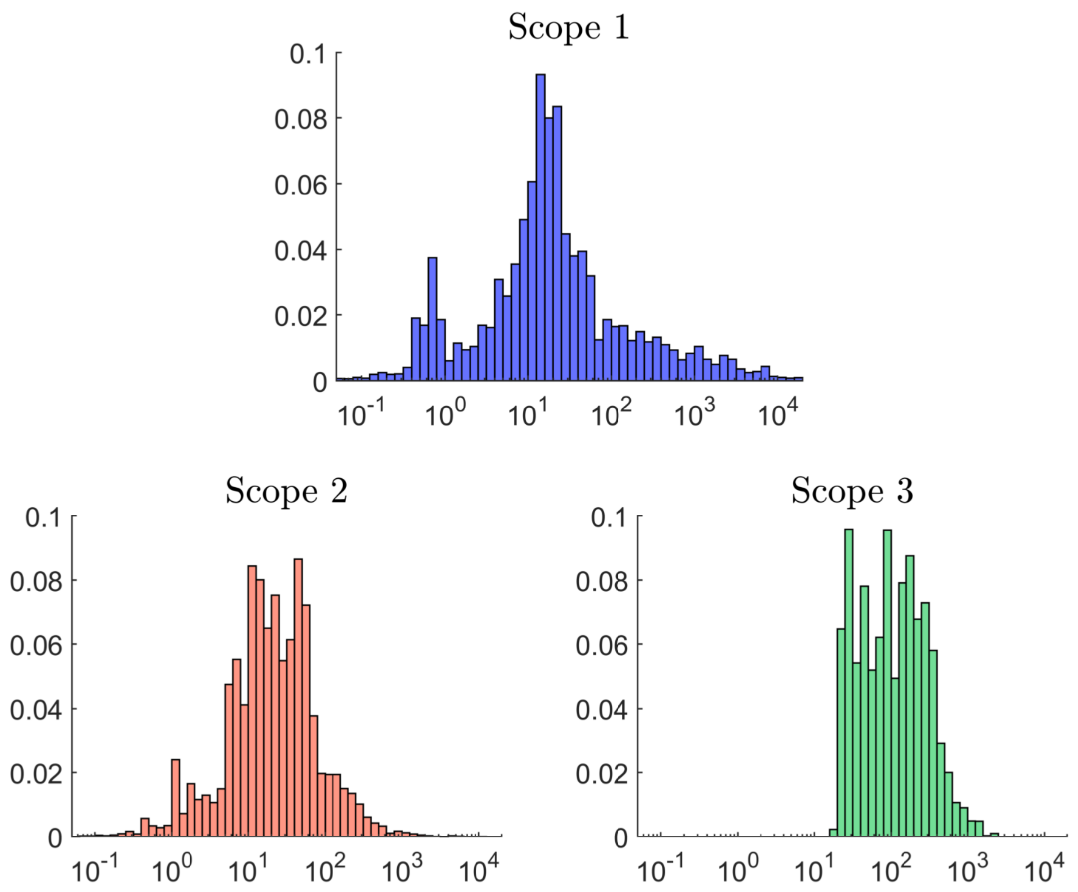
Two main approaches:

1. **Generic** carbon intensity per $
   1. Revenue: $CO_2e/\$$
   2. Enterprise value including cash (EVIC): $CO_2e/\$$
2. **Physical** carbon intensity per production unit
   1. Transport sector (aviation): $CO_2e/RPK$ (revenue passenger kilometers)
   2. Transport sector (shipping): $CO_2e/RTK$ (revenue ton kilometers)
   3. Industry (cement): $CO_2e/t$ cement (ton of cement)
   4. Industry (steel): $CO_2e/t$ steel (ton of steel)
   5. Electricity: $CO_2e/MWh$ (megawatt hour)
   6. Buildings: $CO_2e/SQM$ (square meter)

$\Rightarrow$ In what follows, we use the revenues to normalize carbon emissions

# Carbon intensity

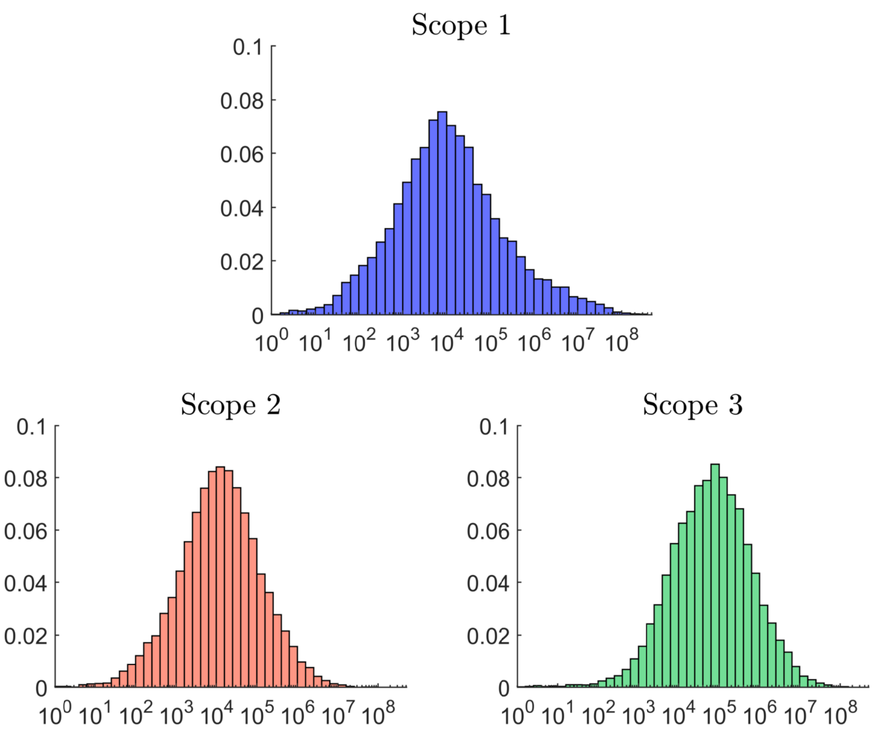
Figure 21: Histogram of carbon intensity (log scale, $tCO_2e$/$ mn)



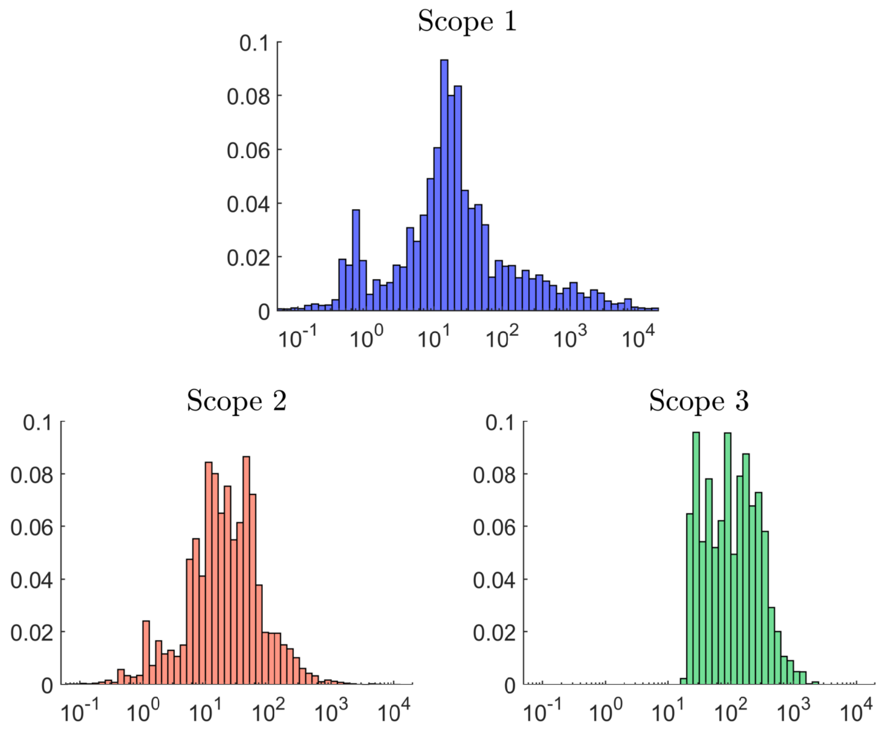

Source: Trucost reporting year 2019 & Le Guenedal and Roncalli (2022).

# Carbon intensity

## Carbon emissions




## Carbon intensity



# Carbon intensity

Table 7: Examples of carbon emissions and intensity

| Company | Emission (in $tCO_2e$) | | | Revenue | Intensity (in $tCO_2e$/\$ mn) | | |
|---|---|---|---|---|---|---|---|
| | Scope 1 | Scope 2 | Scope 3 | (in \$ mn) | Scope 1 | Scope 2 | Scope 3 |
| Alphabet | 74 462 | 5 116 949 | 7 166 240 | 161 857 | 0.460 | 31.614 | 44.275 |
| Amazon | 5 760 000 | 5 500 000 | 20 054 722 | 280 522 | 20.533 | 19.606 | 71.491 |
| Apple | 50 463 | 862 127 | 27 618 943 | 260 174 | 0.194 | 3.314 | 106.156 |
| BP | 49 199 999 | 5 200 000 | 103 840 194 | 276 850 | 177.714 | 18.783 | 375.077 |
| Danone | 722 122 | 944 877 | 28 969 780 | 28 308 | 25.509 | 33.378 | 1023.365 |
| Enel | 69 981,891 | 5 365 386 | 8 726 973 | 86 610 | 808.016 | 61.949 | 100.762 |
| Juventus | 6 665 | 15 739 | 35 842 | 709 | 9.401 | 22.198 | 50.553 |
| LVMH | 67 613 | 262 609 | 11 853 749 | 60 083 | 1.125 | 4.371 | 197.291 |
| Microsoft | 113 414 | 3 556 553 | 5 977 488 | 125 843 | 0.901 | 28.262 | 47.500 |
| Nestle | 3 291 303 | 3 206 495 | 61 262 078 | 93 153 | 35.332 | 34.422 | 657.647 |
| Netflix | 38 481 | 145 443 | 1 900 283 | 20 156 | 1.909 | 7.216 | 94.277 |
| Total | 40 909 135 | 3 596 127 | 49 831 487 | 200 316 | 204.223 | 17.952 | 248.764 |
| Volkswagen | 4 494 066 | 5 973 894 | 65 335 372 | 282 817 | 15.890 | 21.123 | 231.016 |

Source: Trucost reporting year 2019.

# Carbon intensity

Table 8: Statistics of carbon emissions and intensity

| Scope | Emission (in $10^6 \cdot tCO_2e$) | | | | Intensity (in $10^3 \cdot tCO_2e/\$$ mn) | | | |
|---|---|---|---|---|---|---|---|---|
| | Avg. | Med. | $Q$ (95%) | Max. | Avg. | Med. | $Q$ (95%) | Max. |
| 1 | 0.992 | 0.010 | 2.28 | 587.1 | 0.277 | 0.016 | 1.14 | 207.4 |
| 2 | 0.156 | 0.012 | 0.53 | 99.1 | 0.053 | 0.021 | 0.19 | 11.9 |
| 3 | 0.648 | 0.067 | 2.50 | 137.5 | 0.170 | 0.099 | 0.51 | 2.0 |

Source: Trucost reporting year 2019 & Le Guenedal and Roncalli (2022).

# Carbon intensity

Table 9: Rank correlation matrix (in %) of carbon metrics

| | $\mathcal{CE}_1$ | $\mathcal{CE}_2$ | $\mathcal{CE}_3$ | $\mathcal{CI}_1$ | $\mathcal{CI}_2$ | $\mathcal{CI}_3$ |
|---|---|---|---|---|---|---|
| $\mathcal{CE}_1$ | 100.0 | | | | | |
| $\mathcal{CE}_2$ | 78.1 | 100.0 | | | | |
| $\mathcal{CE}_3$ | 81.9 | 81.9 | 100.0 | | | |
| $\mathcal{CI}_1$ | 70.3 | 32.8 | 32.0 | 100.0 | | |
| $\mathcal{CI}_2$ | 38.0 | 55.3 | 18.1 | 54.4 | 100.0 | |
| $\mathcal{CI}_3$ | 55.5 | 36.6 | 55.6 | 66.6 | 44.7 | 100.0 |

Source: Trucost reporting year 2019 & Le Guenedal and Roncalli (2022).

# Carbon intensity

## Additivity property

Carbon intensity is additive when we consider a given issuer:

$$\begin{aligned} \mathcal{CI}_{i,1+2+3} &= \frac{\mathcal{CE}_{i,1} + \mathcal{CE}_{i,2} + \mathcal{CE}_{i,3}}{Y_i} \\ &= \mathcal{CI}_{i,1} + \mathcal{CI}_{i,2} + \mathcal{CI}_{i,3} \end{aligned}$$

# Carbon intensity

**The additivity property is not satisfied when we consider a set of issuers**

- We consider a portfolio $x$ invested in $n$ assets. We have:

$$\mathcal{CE}_j(x) = \sum_{i=1}^{n} \frac{W_i}{\mathcal{MV}_i} \cdot \mathcal{CE}_{i,j} = \sum_{i=1}^{n} \varpi_i \cdot \mathcal{CE}_{i,j}$$

where $\mathcal{MV}_i$ is the market value of the company $i$, $W_i$ is the dollar value invested in the company $i$ and $\varpi_i$ is the ownership ratio:

$$\varpi_i = \frac{W_i}{\mathcal{MV}_i}$$

- Let $x_i$ be the weight of the company $i$. We have:

$$W_i = x_i \cdot W$$

where $W = \sum_{i=1}^{n} W_i$ is the dollar value of the portfolio

# Carbon intensity

- We also have:

$$\varpi_i = \frac{W_i}{\mathcal{MV}_i} = \frac{x_i \cdot W}{\mathcal{MV}_i}$$

- We deduce that:

$$\mathcal{CE}_j(x) = W \cdot \left( \sum_{i=1}^{n} x_i \cdot \frac{\mathcal{CE}_{i,j}}{\mathcal{MV}_i} \right) = W \cdot \left( \sum_{i=1}^{n} x_i \cdot \mathcal{CI}_{i,j}^{\mathcal{MV}} \right)$$

where $\mathcal{CI}_{i,j}^{\mathcal{MV}}$ is the carbon intensity, where the normalization factor is the market value of the company:

$$\mathcal{CI}_{i,j}^{\mathcal{MV}} = \frac{\mathcal{CE}_{i,j}}{\mathcal{MV}_i}$$

- $\mathcal{CE}_j(x)$ is generally expressed generally in tCO2e per 1\$ mn invested ($W = \$10^6$)

# Carbon intensity

- The weighted-average carbon intensity (WACI) is equal to:

$$\mathcal{CI}_j(x) = \sum_{i=1}^{n} x_i \cdot \mathcal{CI}_{i,j}$$

$\Rightarrow$ The two equations are mutually satisfied $\Leftrightarrow Y_i \propto \mathcal{MV}_i$

# Carbon intensity

- The exact value of the carbon intensity is:

$$\mathcal{CI}_j(x) = \frac{\mathcal{CE}_j(x)}{Y(x)} = \sum_{i=1}^{n} \omega_i \cdot \mathcal{CI}_{i,j}$$

where:

$$Y(x) = W \cdot \left( \sum_{i=1}^{n} x_i \cdot \frac{Y_i}{\mathcal{MV}_i} \right)$$

and:

$$\omega_i = \frac{x_i \cdot \dfrac{Y_i}{\mathcal{MV}_i}}{\sum_{k=1}^{n} x_k \cdot \dfrac{Y_k}{\mathcal{MV}_k}}$$

# Carbon intensity

**Example**

- We assume that $\mathcal{CE}_{1,j} = 5 \times 10^6$, $Y_1 = 2 \times 10^5$, $\mathcal{MV}_1 = 10^7$, $\mathcal{CE}_{2,j} = 5 \times 10^7$, $Y_2 = 4 \times 10^6$ and $\mathcal{MV}_2 = 10^7$
- We deduce that $\mathcal{CI}_{1,j} = 25.0$ and $\mathcal{CI}_{2,j} = 12.5$
- We invest $W = \$10$ mn

We have:

$$\left\{ \begin{array}{l} \mathcal{CE}_j(x) = W \cdot \left( x_1 \cdot \dfrac{\mathcal{CE}_{1,j}}{\mathcal{MV}_1} + x_2 \cdot \dfrac{\mathcal{CE}_{2,j}}{\mathcal{MV}_2} \right) \\ Y(x) = W \cdot \left( x_1 \cdot \dfrac{Y_1}{\mathcal{MV}_1} + x_2 \cdot \dfrac{Y_2}{\mathcal{MV}_2} \right) \\ \mathcal{CI}_j(x) = x_1 \cdot \mathcal{CI}_{1,j} + x_2 \cdot \mathcal{CI}_{2,j} \end{array} \right.$$

# Carbon intensity

## Example

- We assume that $\mathcal{CE}_{1,j} = 5 \times 10^6$, $Y_1 = 2 \times 10^5$, $\mathcal{MV}_1 = 10^7$, $\mathcal{CE}_{2,j} = 5 \times 10^7$, $Y_2 = 4 \times 10^6$ and $\mathcal{MV}_2 = 10^7$
- We deduce that $\mathcal{CI}_{1,j} = 25.0$ and $\mathcal{CI}_{2,j} = 12.5$
- We invest $W = \$10$ mn

| $x_1$ | $x_2$ | $\mathcal{CE}_j(x)$ (in $10^6$) | $Y(x)$ (in $10^6$) | $\dfrac{\mathcal{CE}_j(x)}{Y(x)}$ | $\mathcal{CI}_j(x)$ |
|---|---|---|---|---|---|
| 0% | 100% | 50.00 | 4.00 | 12.50 | 12.50 |
| 10% | 90% | 45.50 | 3.62 | 12.57 | 13.75 |
| 20% | 80% | 41.00 | 3.24 | 12.65 | 15.00 |
| 30% | 70% | 36.50 | 2.86 | 12.76 | 16.25 |
| 50% | 50% | 27.50 | 2.10 | 13.10 | 18.75 |
| 70% | 30% | 18.50 | 1.34 | 13.81 | 21.25 |
| 80% | 20% | 14.00 | 0.96 | 14.58 | 22.50 |
| 90% | 10% | 9.50 | 0.58 | 16.38 | 23.75 |
| 100% | 0% | 5.00 | 0.20 | 25.00 | 25.00 |

# The M&A puzzle

## Example

- We assume that $\mathcal{CE}_{1,j} = 5 \times 10^6$, $Y_1 = 2 \times 10^5$, $\mathcal{MV}_1 = 10^7$, $\mathcal{CE}_{2,j} = 5 \times 10^7$, $Y_2 = 4 \times 10^6$ and $\mathcal{MV}_2 = 10^7$
- We deduce that $\mathcal{CI}_{1,j} = 25.0$ and $\mathcal{CI}_{2,j} = 12.5$
- We buy the two companies $\Rightarrow W = \$20$ mn, $x_1 = 50\%$ and $x_2 = 50\%$

| $W$ (in $10^6$) | $x_1$ | $x_2$ | $\mathcal{CE}_j(x)$ (in $10^6$) | $Y(x)$ (in $10^6$) | $\dfrac{\mathcal{CE}_j(x)}{Y(x)}$ | $\mathcal{CI}_j(x)$ |
|---|---|---|---|---|---|---|
| 10 | 0% | 100% | 50.00 | 4.00 | 12.50 | 12.50 |
| 10 | 100% | 0% | 5.00 | 0.20 | 25.00 | 25.00 |
| 20 | 50% | 50% | 55.00 | 4.20 | 13.10 | 18.75 |

# Carbon transition pathway

## Net Zero Carbon Emissions

- Carbon neutrality
- Reduction scenario
- Carbon trajectories
  - Carbon trend
  - Reduction targets
  - Specific NZE scenario
- Temperature tags

# Carbon reduction scenario

- IPCC report urges action to drastically reduce carbon emissions to net zero by 2050
- The carbon reduction trajectory imposes a reduction of total emissions by at least 7% every year between 2019 and 2050
- International Energy Agency (IEA) NZE scenario
  - This scenario implies a 40.11% reduction of carbon emissions in 2030 and 61.84% in 2035
  - In 2050, gross emissions would be 1.94 $GtCO_2e$ offset by the carbon capture and storage (CCS) technology

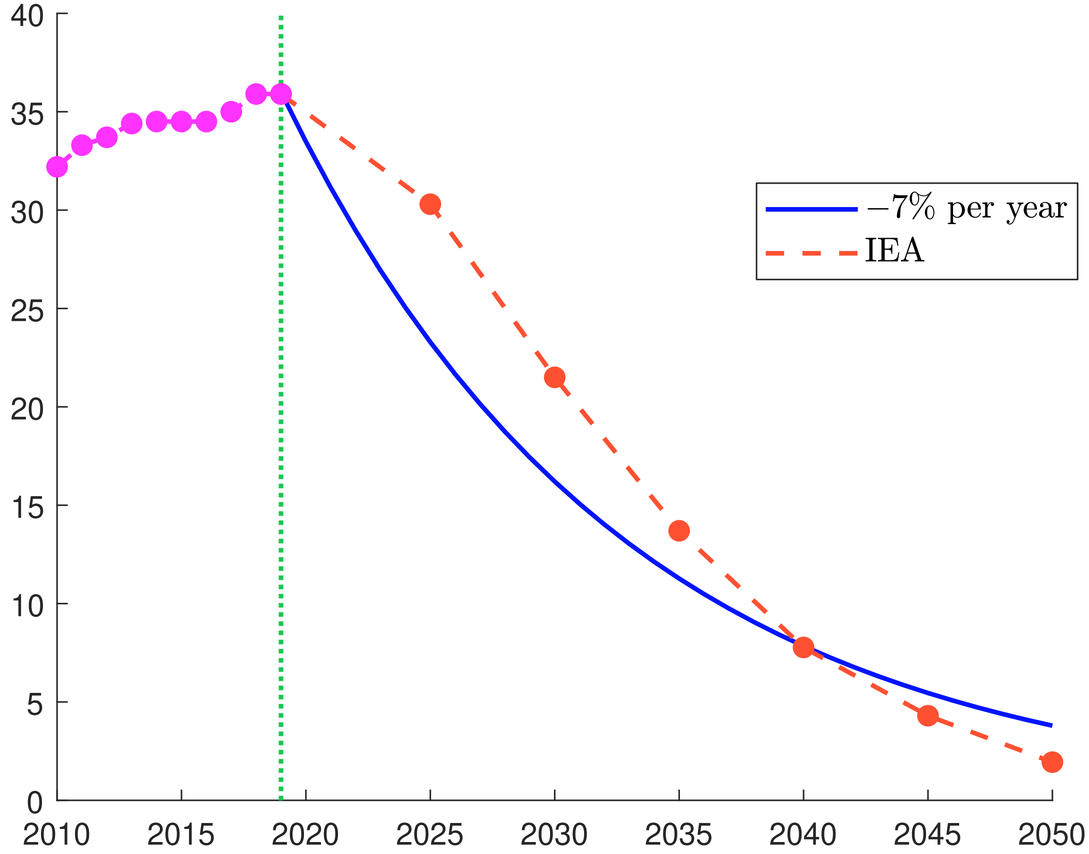
Table 10: IEA NZE scenario (in $GtCO_2e$)

| Year | 2019 | 2025 | 2030 | 2035 | 2040 | 2045 | 2050 |
|---|---|---|---|---|---|---|---|
| Gross emission | 35.90 | 30.30 | 21.50 | 13.70 | 7.77 | 4.30 | 1.94 |
| CCS | 0.00 | −0.06 | −0.32 | −0.96 | −1.46 | −1.80 | −1.94 |
| Net emission | 35.90 | 30.24 | 21.18 | 12.74 | 6.31 | 2.50 | 0.00 |
| Reduction (in %) | 0.00 | 15.60 | 40.11 | 61.84 | 78.36 | 88.02 | 94.60 |

Source: IEA (2021, Chapter 2, Figure 2.3, page 55).

# Carbon reduction scenario

Figure 22: Two net zero emission scenarios




Source: IEA (2021) & Le Guenedal and Roncalli (2022).

# Carbon trend

- We have:

$$\mathcal{CE}_i(t) = \beta_{i,0} + \beta_{i,1} t + u_i(t)$$

- The parameters $\beta_{i,0}$ and $\beta_{i,1}$ are estimated using the OLS method
- The carbon trajectory implied by the current trend is equal to:

$$\mathcal{CE}_i^{Trend}(t) := \widehat{\mathcal{CE}}_i(t) = \hat{\beta}_{i,0} + \hat{\beta}_{i,1} t$$

# Carbon trend

## Example

We consider the company $\boldsymbol{\Lambda}$ and the direct carbon emissions (scope 1) in $MtCO_2e$:

| Year | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 |
|---|---|---|---|---|---|---|---|
| $\mathcal{CE}_{i,1}(t)$ | 57.80 | 58.46 | 57.90 | 55.13 | 51.63 | 46.34 | 47.09 |
| Year | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 |
| $\mathcal{CE}_{i,1}(t)$ | 46.08 | 44.37 | 41.75 | 39.40 | 36.26 | 40.71 | 40.91 |

Source: Trucost reporting year 2019.

# Carbon trend

- We have:

$$Y = \begin{pmatrix} 57.80 \\ 58.46 \\ \vdots \\ 40.71 \\ 40.91 \end{pmatrix} \quad \text{and} \quad X = \begin{pmatrix} 1 & 2006 \\ 1 & 2007 \\ \vdots & \vdots \\ 1 & 2018 \\ 1 & 2019 \end{pmatrix}$$

and:

$$\hat{\beta} = \left(X^\top X\right)^{-1} X^\top Y = \begin{pmatrix} 3479.77 \\ -1.7055 \end{pmatrix}$$

- We obtain $\hat{\beta}_0 = 3479.77$ and $\hat{\beta}_1 = -1.7055$. We deduce that:

$$\begin{aligned} \mathcal{CE}_{i,1}^{\mathrm{trend}}(t) &= 3479.77 - 1.7055 \cdot t \\ &= 3479.77 - 1.7055 \cdot (2019 + h) \\ &= 36.33 - 1.7055 \cdot h \end{aligned}$$

and $\mathcal{CE}_{i,1}^{\mathrm{trend}}(2020) = 34.62$, $\mathcal{CE}_{i,1}^{\mathrm{trend}}(2021) = 32.92$, $\mathcal{CE}_{i,1}^{\mathrm{trend}}(2030) = 17.57$, $\mathcal{CE}_{i,1}^{\mathrm{trend}}(2040) = 0.51$, etc.

# Carbon targets

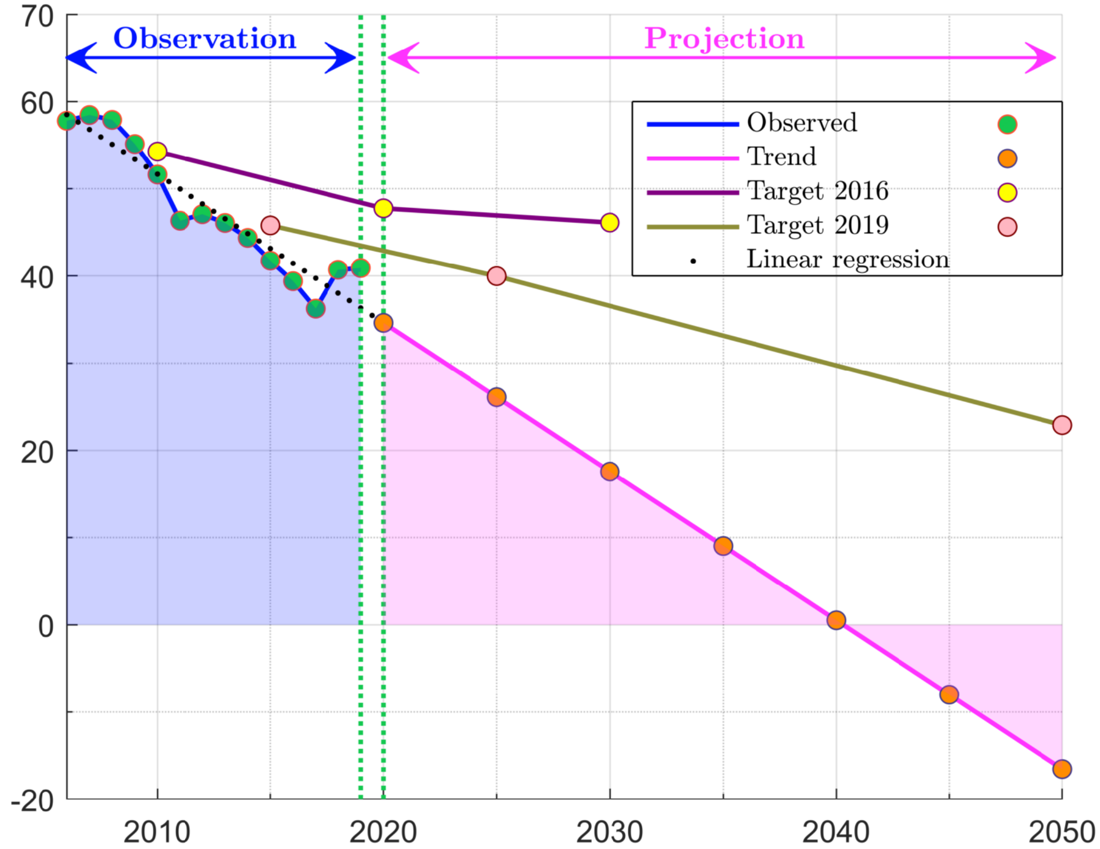
## Corporate commitments/pledges

- Companies can directly disclose carbon targets $\mathcal{CE}_{i,j}^{\mathrm{target}}(t)$ at a given horizon date $t$ for a given scope $j$
- CDP gathers information about reduction targets (base year, target year, target value, scope, percentage of the scope concerned, etc.)

- The company $\boldsymbol{\Lambda}$ has disclosed reduction targets in 2016 and 2019
- We observe that the 2019 targets are more ambitious than the 2016 targets

# Carbon trajectories

Figure 23: Scope 1 trajectory of the company $\Lambda$ (in $MtCO_2e$)




Source: Carbon Disclosure Project reporting year 2019 & Le Guenedal and Roncalli (2022).

# Implied temperature

- Temperature tags are indicators assigned to companies by mixing various metrics
- Based on the carbon reduction required to achieve a climate scenario, and individual trajectories, it is possible to interpolate a temperature for each issuer
- Each provider has its own methodology:
    - Carbon Disclosure Project (CDP)
    - Iceberg Data Lab
    - Science Based Target initiative (SBTi)
    - Trucost

# Implied temperature

Table 11: Global temperature changes in % (wrt year 2005)

| Scenario | 2010 | 2020 | 2030 | 2040 | 2050 |
|---|---|---|---|---|---|
| $1.5°\mathrm{C}$ (SSP2, RCP 1.9W/$m^2$) | +7.5% | 17.1% | −28.6% | −63.9% | −87.3% |
| $1.8°\mathrm{C}$ (SSP2, RCP 2.6W/$m^2$) | +8.1% | 17.4% | −14.5% | −34.5% | −51.5% |
| $2.2°\mathrm{C}$ (SSP2, RCP 3.4W/$m^2$) | +8.1% | 19.9% | +8.2% | −5.8% | −20.6% |
| $3.0°\mathrm{C}$ (SSP2, RCP 4.5W/$m^2$) | +8.1% | 21.5% | +24.4% | +22.2% | +11.3% |
| $4.0°\mathrm{C}$ (SSP2, RCP 6.0W/$m^2$) | +8.1% | 22.2% | +33.6% | +42.7% | +45.9% |
| $5.0°\mathrm{C}$ (SSP2, Baseline) | +8.1% | 26.8% | +43.7% | +58.7% | +70.0% |

Source: SSP Database (Shared Socioeconomic Pathways), Version 2.0.

If we would like to achieve a $1.8°\mathrm{C}$ scenario, this implies reducing absolute carbon emissions with respect to year 2005 by 51.5%

# Implied temperature

Table 12: Frequency of temperature ratings (in %)

| Range | CDP Scope 1 + 2 + 3 | CDP Short term | CDP Mid term | CDP Long term | Iceberg |
|---|---|---|---|---|---|
| $\mathcal{T} \leq 1.0°\mathrm{C}$ | 0.00 | 0.00 | 0.00 | 0.00 | 1.01 |
| $1.0°\mathrm{C} < \mathcal{T} \leq 1.5°\mathrm{C}$ | 1.44 | 2.92 | 10.68 | 2.71 | 2.60 |
| $1.5°\mathrm{C} < \mathcal{T} \leq 2.0°\mathrm{C}$ | 6.20 | 1.26 | 13.03 | 3.94 | 3.14 |
| $2.0°\mathrm{C} < \mathcal{T} \leq 2.5°\mathrm{C}$ | 6.86 | 3.07 | 7.46 | 2.68 | 21.76 |
| $2.5°\mathrm{C} < \mathcal{T} \leq 3.0°\mathrm{C}$ | 7.64 | 1.99 | 4.21 | 0.48 | 30.87 |
| $3.0°\mathrm{C} < \mathcal{T} \leq 3.5°\mathrm{C}$ | 76.95 | 89.77 | 62.80 | 90.07 | 32.30 |
| $3.5°\mathrm{C} < \mathcal{T} \leq 4.0°\mathrm{C}$ | 0.78 | 0.81 | 1.44 | 0.09 | 2.23 |
| $4.0°\mathrm{C} < \mathcal{T} \leq 4.5°\mathrm{C}$ | 0.12 | 0.18 | 0.36 | 0.03 | 3.31 |
| $4.5°\mathrm{C} < \mathcal{T} \leq 5.0°\mathrm{C}$ | 0.00 | 0.00 | 0.00 | 0.00 | 0.77 |
| $\mathcal{T} = 3.2°\mathrm{C}$ | 52.09 | 88.50 | 61.39 | 89.95 | 0.01 |

Source: CDP Temperature Ratings Dataset, version 1.1, February 2021 & Iceberg Data Lab (2021).

# Climate transition risk

**Definition**

- Transition risks arise from the sudden shift towards a low-carbon economy
- Such transitions could mean that some sectors of the economy face big shifts in asset values or higher costs of doing business

*"It's not that policies stemming from deals like the Paris Climate Agreement are bad for our economy — in fact, the risk of delaying action altogether would be far worse. Rather, it's about the speed of transition to a greener economy — and how this affects certain sectors and financial stability" (Bank of England, 2021)*

# Climate transition risk

The previous approach assumes that the **climate-related market risk** of a company is measured by its **current carbon intensity**

...But the **market perception** of the climate change may be different

# Climate transition risk

## Fundamental-based analysis

- Carbon footprint and pathway are measured by $CO_2$ emissions
- They are fundamental data

## Market-based analysis

- Financial market's perception of the potentially reduced impact of climate policies' on securities issued by corporations
- These carbon risk metrics use market data
- How an increase in carbon prices and taxes influences the credit risk of the issuer?
- How sensitive the asset price is to a carbon market factor?

# Carbon price

Two main pricing systems:

1. Carbon tax
2. Emissions trading system (ETS)

## Underlying idea

- A high carbon tax impacts the creditworthiness of corporates
- This impact is different from one issuer to another one
- Identifying for each company the carbon price that would lead the default probability in the Merton model to exceed a certain threshold

# Carbon price

Based on the assumptions that the enterprise value $V$ is proportional to the earnings before interest, taxes, depreciation, and amortization (EBITDA) and that the debt $D$ remains constant, we can define the carbon price margin as[7]:

$$\mathcal{CPM}_i = \left(1 - \exp\left(\sigma_i\sqrt{\tau}\Phi\left(-\theta\right) - \left(r + \frac{1}{2}\sigma_i^2\right)\tau\right)\frac{D_i}{V_i}\right)\frac{\mathrm{EBITDA_i}}{\mathcal{CE}_{i,1}}$$

where $\sigma_i$ is the volatility of the enterprise value, $\tau$ is the maturity and $r$ is the risk-free rate

[7] The parameter $\theta$ is the threshold of default probability

# Carbon beta

- Introduced by Harris (2015) and Görgen *et al.* (2019)
- The underlying idea of the carbon beta is to estimate the sensitivity of the stock return with respect to a carbon/climate risk factor
- Climate risk is not only an idiosyncratic risk for the issuer, but also a systematic risk factor like the Fama-French-Carhart market factors

# Carbon price

## Cross-section factor

- Long/short portfolio
- Long on stocks highly exposed to carbon risk
- Short on stocks lowly exposed to carbon risk
- The value of the factor is the return of the L/S portfolio
- High carbon beta = highly exposed to carbon risk

## Time-series factor

- Synthetic index that represents the financial perception of climate risk
- Textual analysis of climate change-related news published by newspapers and media
- High carbon beta = highly exposed to carbon risk

**Risk measure = carbon beta**

# Carbon beta

Let $R_i(t)$ be the return of stock $i$ at time $t$. We assume that:

$$\begin{aligned} R_i(t) &= \alpha_i(t) + \beta_{i,\mathrm{mkt}}(t) R_{\mathrm{mkt}}(t) + \sum_{j=1}^{m} \beta_{i,\mathcal{F}_j}(t) R_{\mathcal{F}_j}(t) + \\ & \quad \boldsymbol{\beta_{i,\mathrm{Carbon}}(t) R_{\mathrm{Carbon}}(t)} + \varepsilon_i(t) \end{aligned}$$

where $R_{\mathrm{mkt}}(t)$ is the return of the market risk factor, $R_{\mathcal{F}_j}(t)$ is the return of the $j^{th}$ alternative risk factor, $R_{\mathrm{Carbon}}(t)$ is the return of the carbon risk factor and $\varepsilon_i(t)$ is a white noise process

**Remark**

*The carbon risk factor corresponds to a long/short portfolio between "green" and "brown" stocks*

# Climate beta

Engle *et al.* (2020) proposed a related approach where the carbon risk factor is replaced by a climate risk news index $\mathcal{I}_{\text{Climate}}$:

$$\begin{aligned} R_i(t) &= \alpha_i(t) + \beta_{i,\text{mkt}}(t) R_{\text{mkt}}(t) + \sum_{j=1}^{m} \beta_{i,\mathcal{F}_j}(t) R_{\mathcal{F}_j}(t) + \\ &\quad \boldsymbol{\beta_{i,\text{Climate}}(t) \mathcal{I}_{\text{Climate}}(t)} + \varepsilon_i(t) \end{aligned}$$

## Remark

*The climate index $\mathcal{I}_{\text{Climate}}$ corresponds to a time series that measures the sentiment about the climate change. It is built using text mining and natural langage processing (NLP)*

# Carbon beta

## The carbon risk factor approach

### Goal

The main objective is to define a **market** measure of carbon risk

### Three-step approach

- Defining a brown green score (BGS) for each stock (scoring model)
- Building a brown minus green factor (Fama-French approach)
- Estimating the carbon beta of a stock with respect to the BMG factor (Multi-factor regression analysis)

Carbon beta = **market** measure of carbon risk

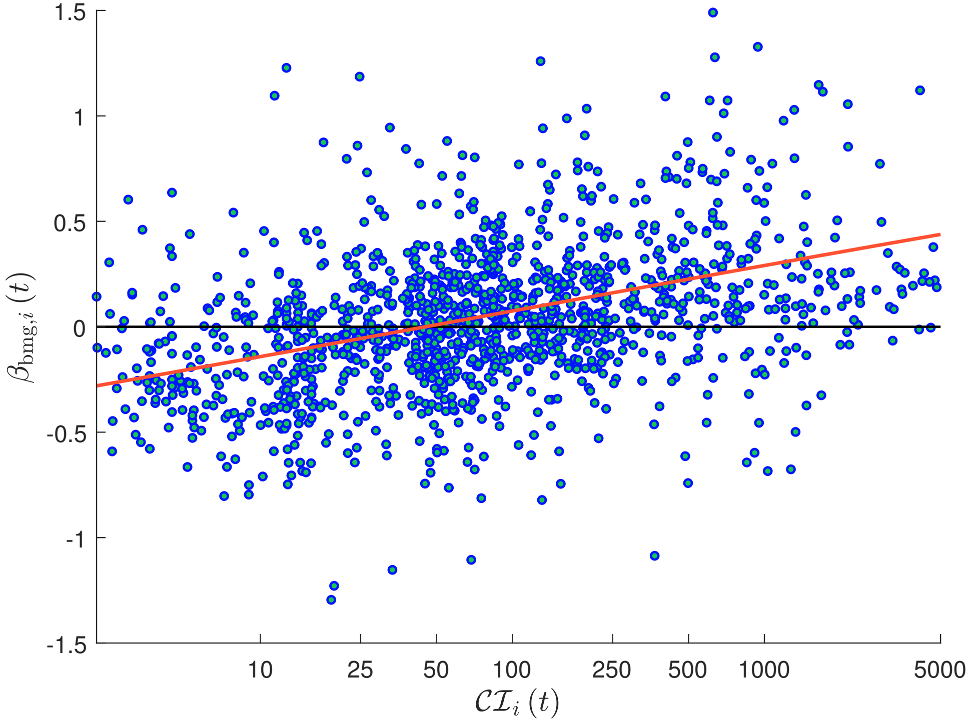
$\neq$

Carbon intensity = **fundamental** measure of carbon risk

# Carbon beta

## The carbon risk factor approach

Figure 24: Market-based vs fundamental-based measures of carbon risk




Source: Roncalli *et al.* (2021).

⇒ The market perception of a carbon risk measure depends on several dimensions: sector, country, etc.

# Carbon beta

## The carbon risk factor approach

**Systematic carbon risk**

- Common risk
- Carbon beta

**Idiosyncratic carbon risk**

- Specific risk
- Carbon intensity

Market measure ($\approx$ general carbon risk exposure, e.g. market repricing risk)

Fundamental measure ($\approx$ specific carbon risk exposure, e.g. reputational risk)

# Carbon beta

## The carbon risk factor approach

| | Green | Neutral | Brown |
|---|---|---|---|
| Small | SG | SN | SB |
| Big | BG | BN | BB |

The BMG factor return $R_{\mathrm{bmg}}(t)$ is derived from the Fama-French method:

$$R_{\mathrm{bmg}}(t) = \frac{1}{2}\left(R_{\mathrm{SB}}(t) + R_{\mathrm{BB}}(t)\right) - \frac{1}{2}\left(R_{\mathrm{SG}}(t) + R_{\mathrm{BG}}(t)\right)$$

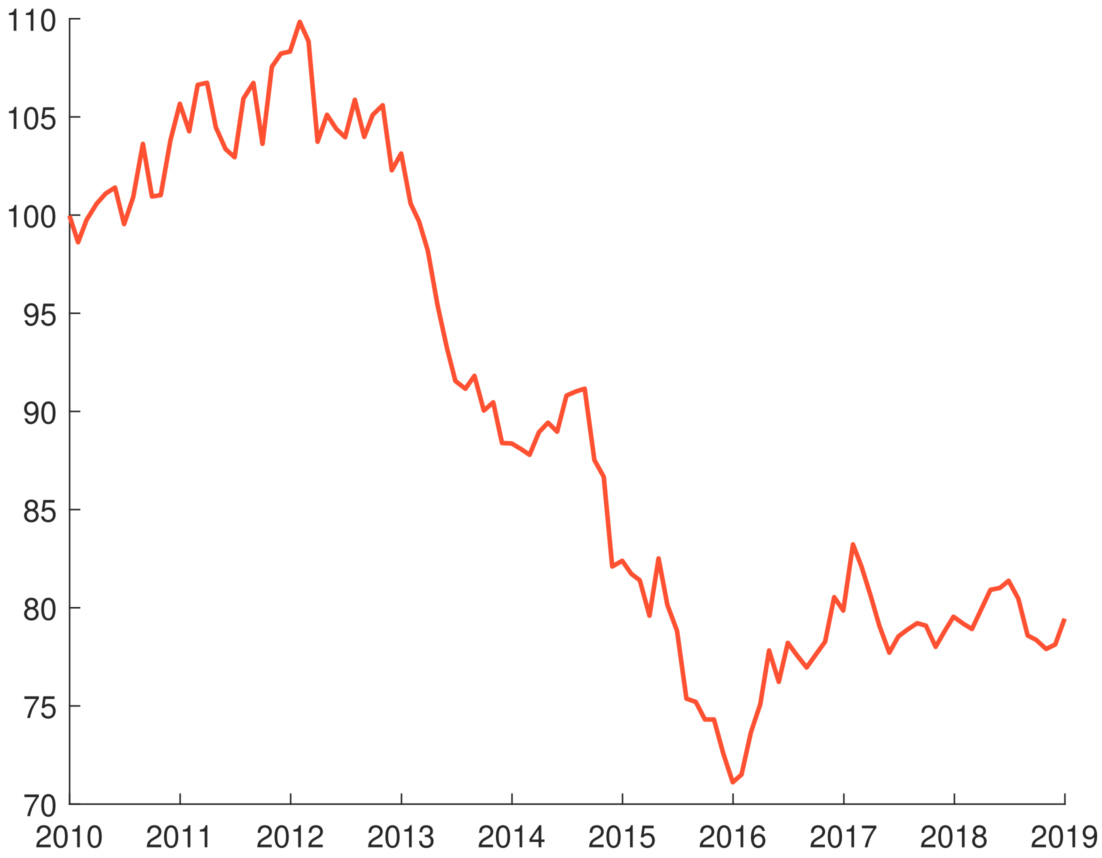
where the returns of each portfolio $R_j(t)$ (small green SG, big green BG, small brown SB, big brown BB) is value-weighted by the market capitalisation

$\Rightarrow$ The BMG factor is a Fama-French risk factor based on a scoring system (brown green score or BGS)

# Carbon beta

## The carbon risk factor approach

Figure 25: Cumulative performance of the BMG factor

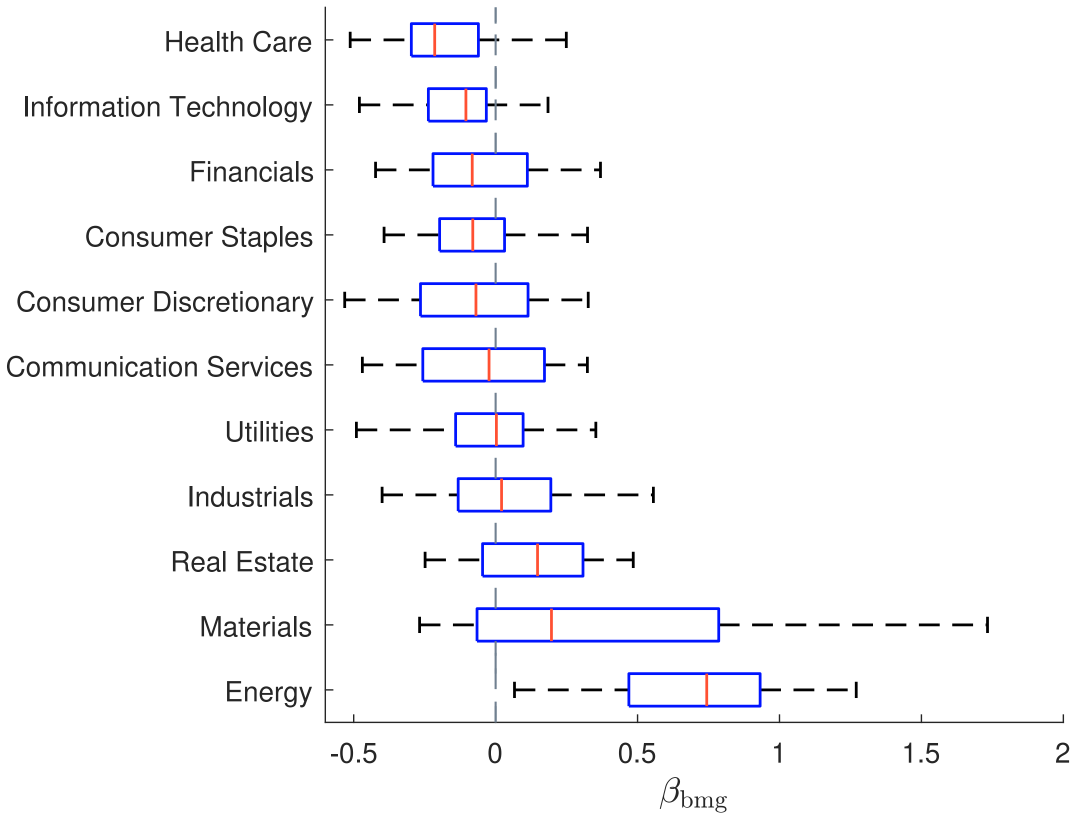



Source: Görgen *et al.* (2019).

# Carbon beta

## The carbon risk factor approach

Figure 26: Box plots of the carbon sensitivities[8]




Source: Roncalli *et al.* (2020).

[8] The box plots provide the median, the quartiles and the 5% and 95% quantiles

# Carbon beta

## The carbon risk factor approach

### Relative carbon risk

- The right measure is $\beta_{\mathrm{bmg}}$
- Sign matters
- **Negative exposure** is preferred

### Absolute carbon risk

- The right measure is $|\beta_{\mathrm{bmg}}|$
- Sign doesn't matter
- **Zero exposure** is preferred

### Two examples

1. We consider three portfolios with a carbon beta of $-0.30$, $-0.05$ and $+0.30$ respectively
2. We consider two portfolios with the following characteristics:
   - The value of the carbon beta is $+0.10$ and the stock dispersion of carbon beta is 0.20
   - The value of the carbon beta is $-0.30$ and the stock dispersion of carbon beta is 1.50

$\Rightarrow$ Impact of portfolio management and theory

# Climate beta

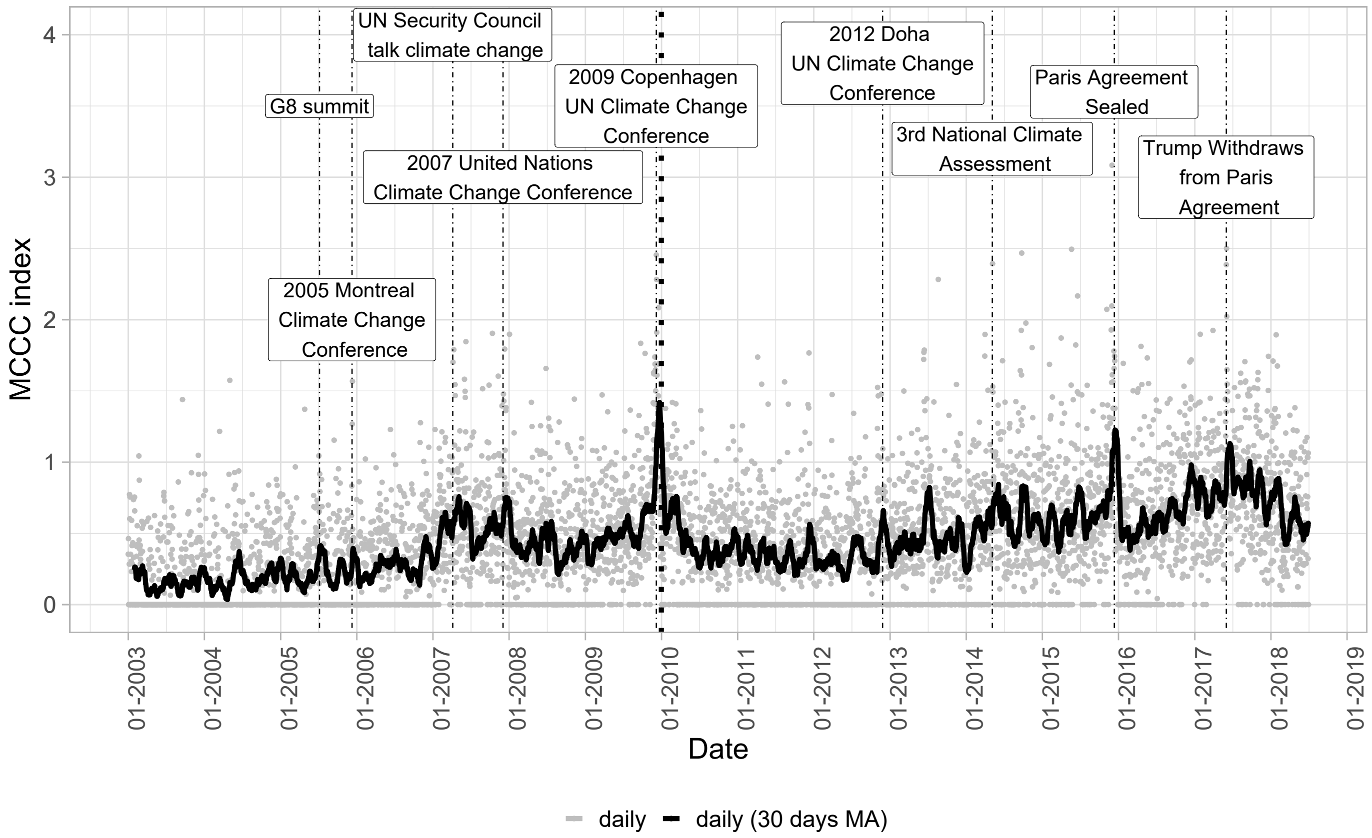
## The climate index approach

- Two main references: Engle *et al.* (2020) & Ardia *et al.* (2021)
- We recall that brown assets must exhibit a positive risk premium
- Nevertheless, "*[...] If ESG concerns strengthen unexpectedly and sufficiently, green assets outperform brown ones despite having lower expected returns*" (Pástor *et al.*, 2021)
- Academics proxy concerns about climate change using climate indices based on news

# Climate beta

## The climate index approach

Figure 27: Media Climate Change Concerns (MCCC) index



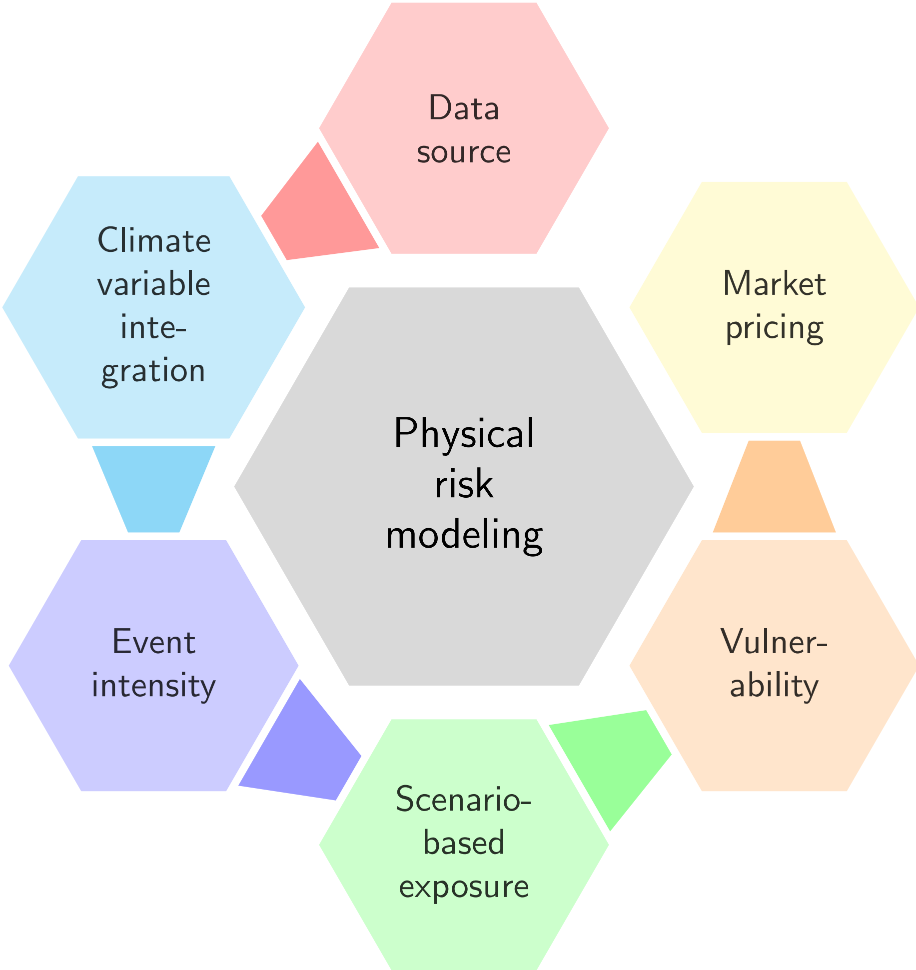

Source: Ardia *et al.* (2021).

# Climate physical risk

*"Responsible investors have paid more attention to the transition risk than to the physical risk. However, recent events show that physical risk is also a big concern. It corresponds to the financial losses that really come from climate change, and not from the adaptation of the economy to prevent them. It includes droughts, floods, storms, etc." (Le Guenedal and Roncalli, 2022).*

# Climate physical risk

Figure 28: Physical risk modeling



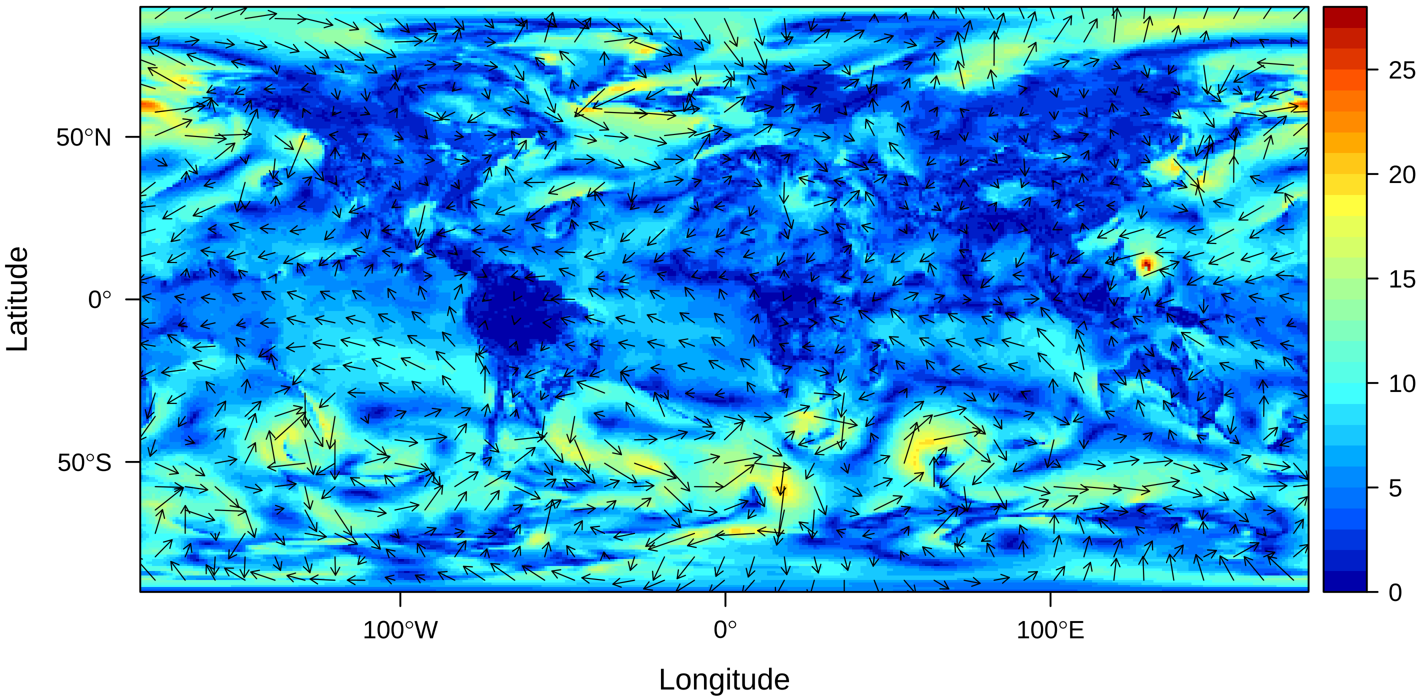
# Climate physical risk

## Climate variable and data source

- The climate data source is the set $\Theta_s = \{\theta(\lambda, \varphi, z, t)\}$
- $\theta = (\theta_1, \ldots, \theta_k)$ is a vector of $k$ climate variables such as temperature, pressure or wind speed
- Each variable $\theta_k$ has four coordinates:
  1. Latitude $\lambda$
  2. Longitude $\varphi$
  3. Height (or altitude) $z$
  4. Time $t$
- Three types of sources:
  1. Meteorological records
  2. Reanalysis
  3. Historical simulations by a climate model

# Climate physical risk

Figure 29: Slice* of wind speed (07/11/2013, tropical cyclone Haiyan)




Source: Modern-Era Retrospective analysis for Research and Applications, Version 2, Global Modeling and Assimilation Office, NASA.

*This is a slice of the MERRA-2 reanalysis at a height of 10 meters on $7^{\text{th}}$ November 2013. The red dot is the location of the eye of the tropical cyclone Haiyan, which affected more than 10 million people in the Philippines

# Climate physical risk

## Event intensity sensitivity

- We first have define the sensitivity of the intensity of extreme events to climate change
- Let $\mathbb{E}\left[I\left(\Theta_s\left(C\right)\right)\right]$ be the expected intensity of the event in the scenario associated with the GHG concentration $C$
- The sensitivity of the event is equal to:

$$\Delta I\left(C\right)=\mathbb{E}\left[I\left(\Theta_s\left(C\right)\right)\right]-I\left(\Theta_s\left(C_0\right)\right)$$

  where $I\left(\Theta_s\left(C_0\right)\right)$ is the current intensity or the reference intensity in a scenario where climate objectives are met
- For instance, we know that the maximum wind of tropical cyclones increases by more than 10% in scenarios with a high GHG concentration

# Climate physical risk

## Asset exposure

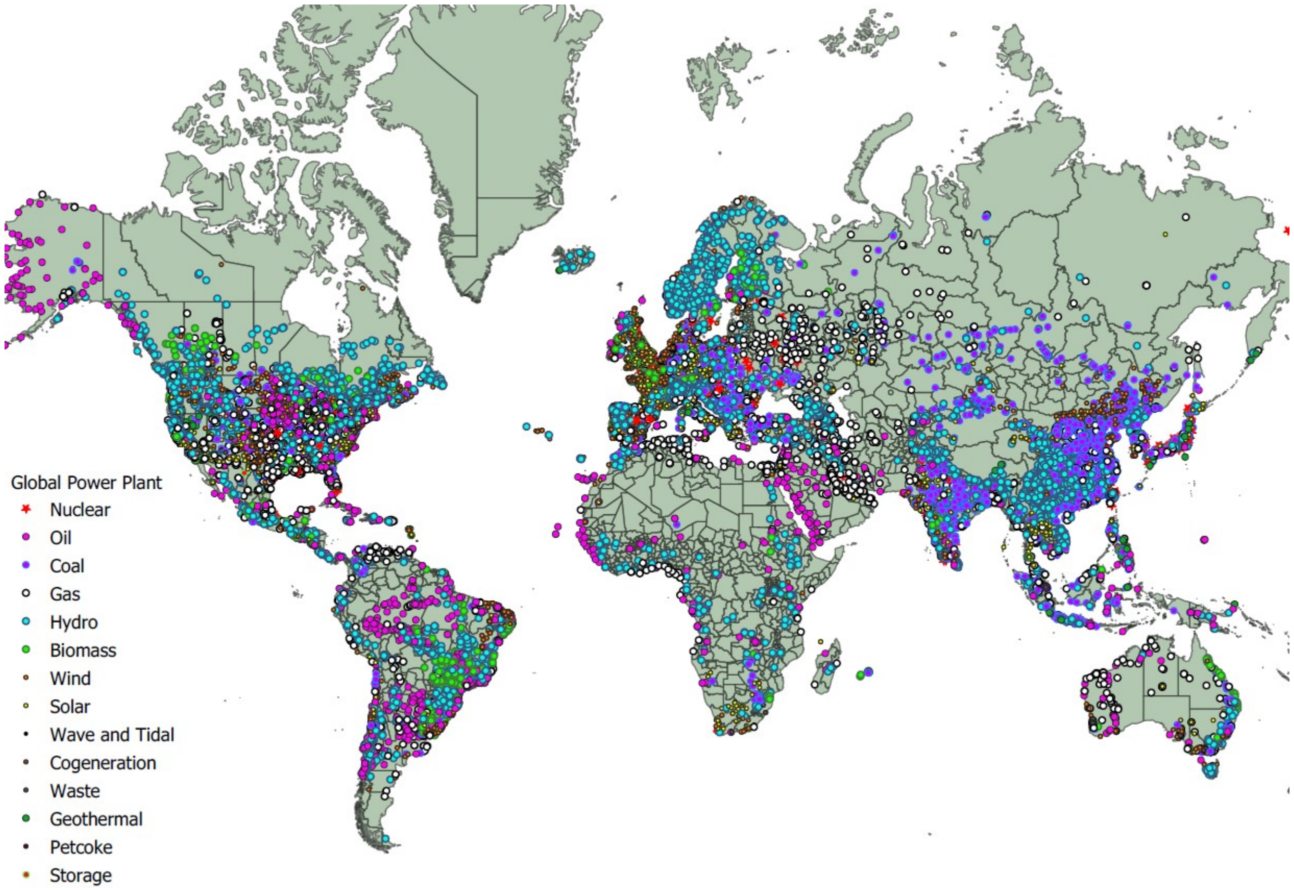
- The asset value of the portfolio can then be written as:

$$\Psi(t) = \sum_{j=1}^{n} x_j \Psi_j(\lambda, \varphi, t)$$

  where $\Psi_j(\lambda, \varphi, t)$ is the geolocated asset value estimated at time $t$ and $x_j$ is the weight of asset $j$ in the portfolio
- This requires the geolocation of the portfolio

# Climate physical risk

Figure 30: Geolocation of world power plants by energy source




Source: Global Power Database version 1.3 (June 2021).

# Climate physical risk

## Vulnerability

- The damage function $\Omega_j(I) \in [0,1]$ is the fraction of property loss with respect to the intensity
- It is generally calibrated on past damages (insurance claims, economic loss, etc.) and disasters

# Climate physical risk

## Market pricing

- The physical risk implied by the concentration scenario $C$ is equal to:

$$\Delta\mathcal{L}oss\left(t,C\right)=\beta\cdot\mathcal{DD}\left(t,C\right)=\beta\sum_{j=1}^{n}x_{j}\Psi_{j}\left(\lambda,\varphi,t\right)\Omega_{j}\left(\Delta I\left(t,C\right)\right)$$

- $\Delta\mathcal{L}oss\left(t,C\right)$ is the relative loss due to the events on the portfolio
- $\beta$ is the transmission factor of the direct damage $\mathcal{DD}\left(t,C\right)$ on the underlying to the loss of financial value in the investment portfolio
- For example, if the facilities of an energy producer are damaged at 50%, the securities issued by this company will be impacted at 50% $\times\ \beta$

# Climate physical risk

## Tropical cyclone damage modeling

Le Guenedal, Drobinski, and Tankov (2021), Measuring and Pricing Cyclone-Related Physical Risk under Changing Climate, *Amundi Working Paper*, `www.ssrn.com/abstract=3850673`

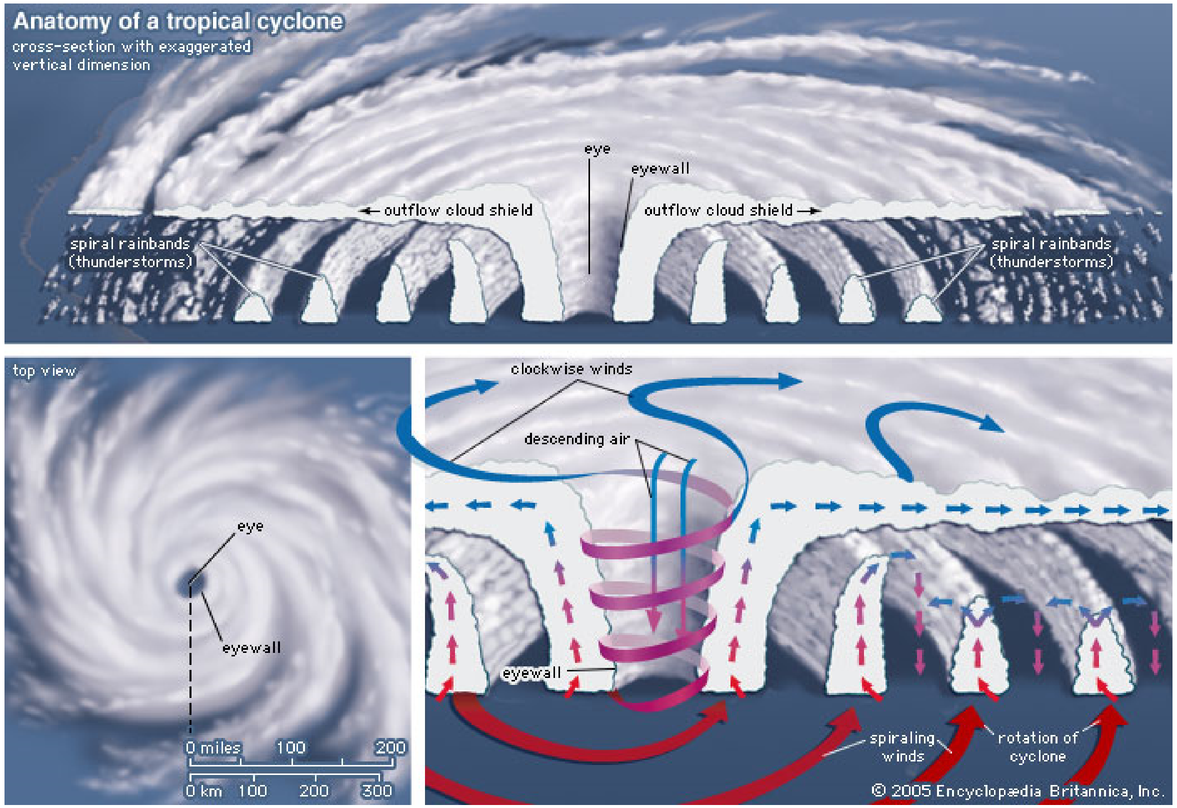
Two main modules:

- Simulation and generation of tropical cyclones under a given climate change scenario
- Geolocation of assets, damage modeling and loss estimation

# Climate physical risk

## Tropical cyclone damage modeling

Figure 31: What is a cyclone?

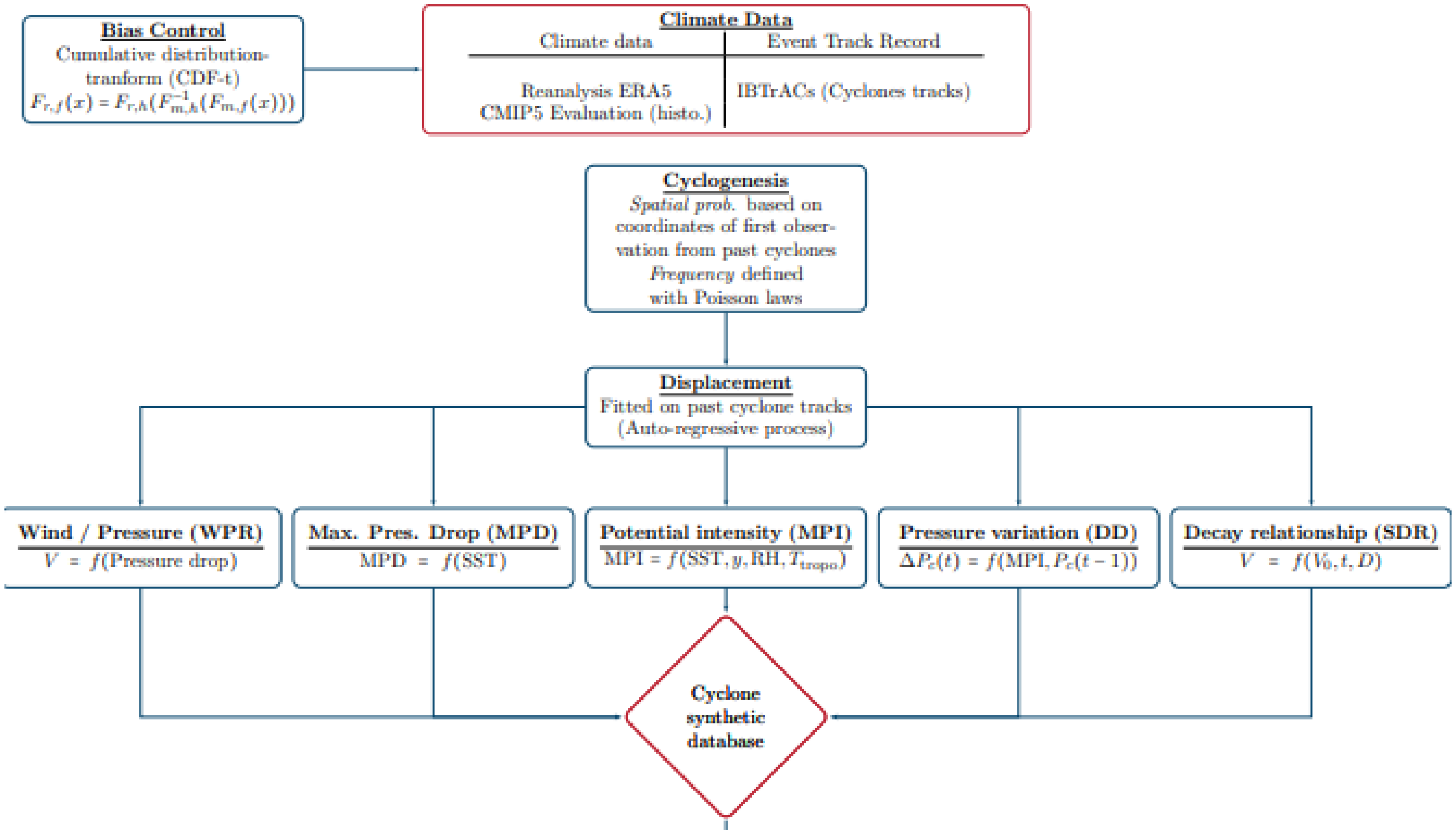



Source: `www.geosci.usyd.edu.au/users/prey/teaching/geos-2111gis/cyclone/cln006.html`

# Climate physical risk

## Tropical cyclone damage modeling

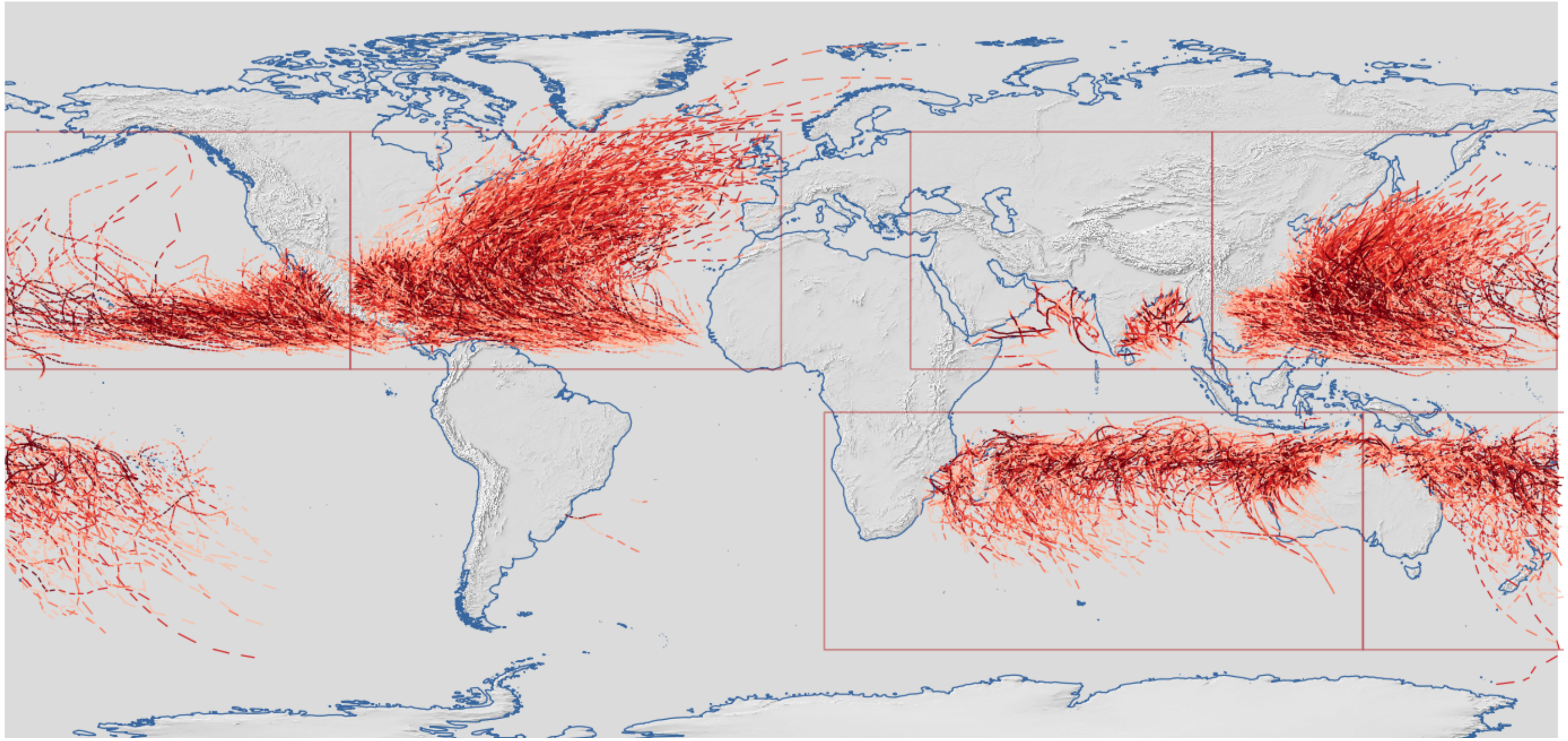
Figure 32: Modeling framework (Module 1)




Source: Le Guenedal *et al.* (2021).

# Climate physical risk
## Tropical cyclone damage modeling

Figure 33: Sample of storms (ERA-5 climate data)



Source: Le Guenedal *et al.* (2021).

# Climate physical risk

## Tropical cyclone damage modeling

### Physics of cyclones

1. Wind pressure relationship (Bloemendaal *et al.*, 2020):

$$V = a\left(P_{\mathrm{env}} - P_c\right)^b$$

2. Maximum potential intensity (Holland, 1997; Emanuel, 1999):

$$MPI = f\left(y, SST, T_{tropo}, MSLP, RH, P_c\right)$$

3. Maximum pressure drop (Bloemendaal *et al.*, 2020):

$$MPD \sim P_{\mathrm{env}} - P_c = A + Be^{C(\mathrm{SST} - T_0)} \qquad T_0 = 30^{o}\mathrm{C}$$

4. Pressure incremental variation (James and Mason, 2005):

$$\begin{array}{rcl} \Delta_t P_c\left(t\right) & = & c_0 + c_1 \Delta_t P_c\left(t-1\right) + c_2 e^{-c_3\left(P_c(t) - MPI(x,y,t)\right)} + \varepsilon\left(P_c, t\right) \\ \varepsilon\left(P_c, t\right) & \sim & \mathcal{N}\left(0, \sigma_{P_c}^2\right) \end{array}$$

5. Decay function (Kaplan and DeMaria, 1995):

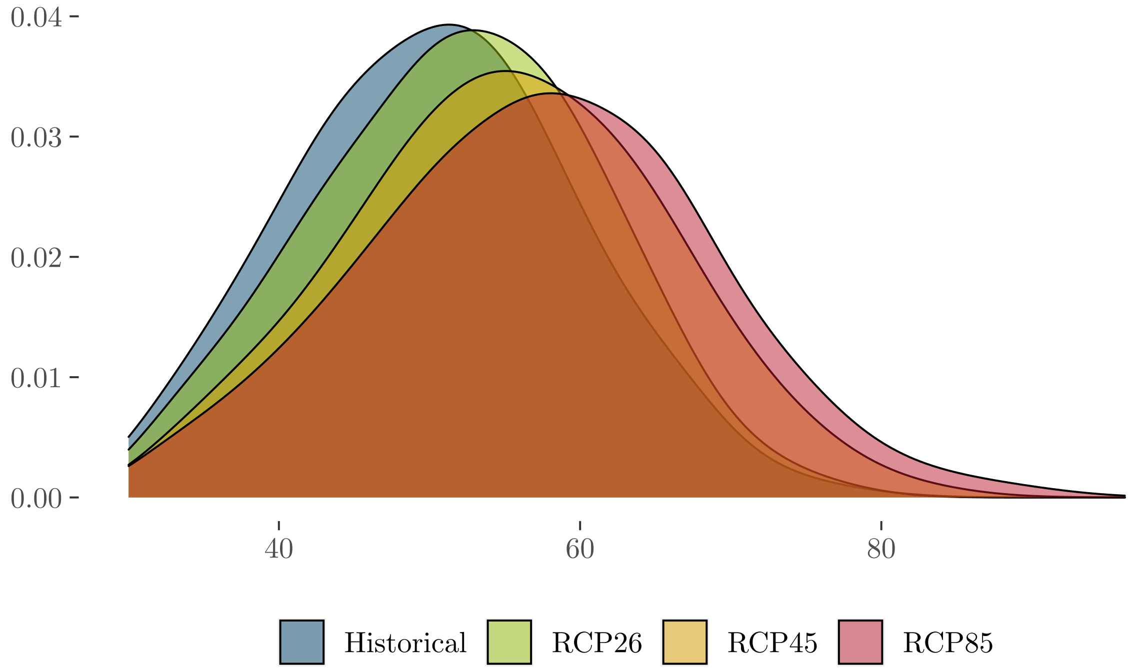
$$V\left(t_L\right) = V_b + (R \cdot V_0 - V_b)e^{-\alpha t} - C$$

where $C = m\left(\ln \frac{D}{D_0}\right) + b$, $m = \tilde{c}_1 t_L\left(t_{0,L} - t_L\right)$ and $b = d_1 t_L\left(t_{0,L} - t_L\right)$

# Climate physical risk

## Tropical cyclone damage modeling

Figure 34: Maximum wind speed in m/s (2070-2100)



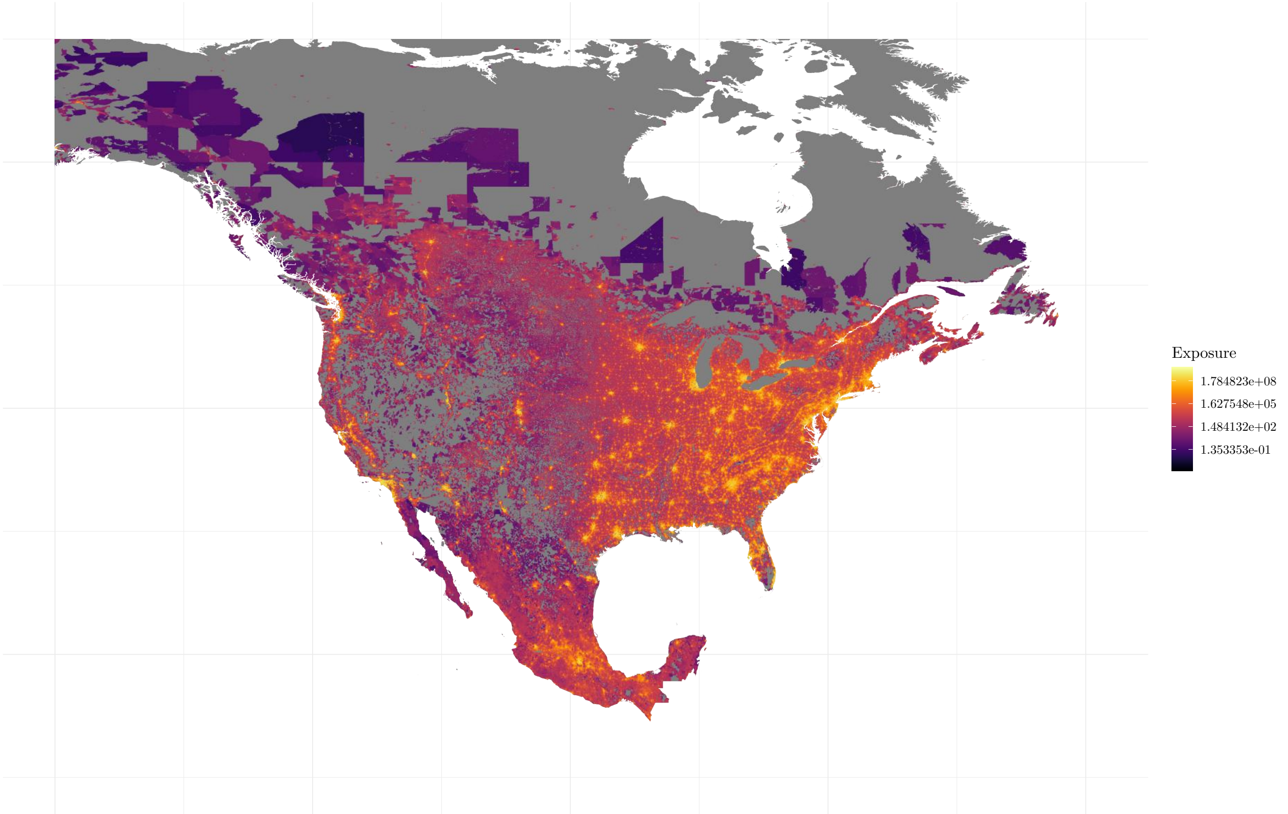

Source: Le Guenedal *et al.* (2021).

**The cyclone simulation database must be sensitive to the climate change scenario**

# Climate physical risk

## Tropical cyclone damage modeling

Figure 35: GDP decomposition of North America (or physical asset values) (Litpop database)

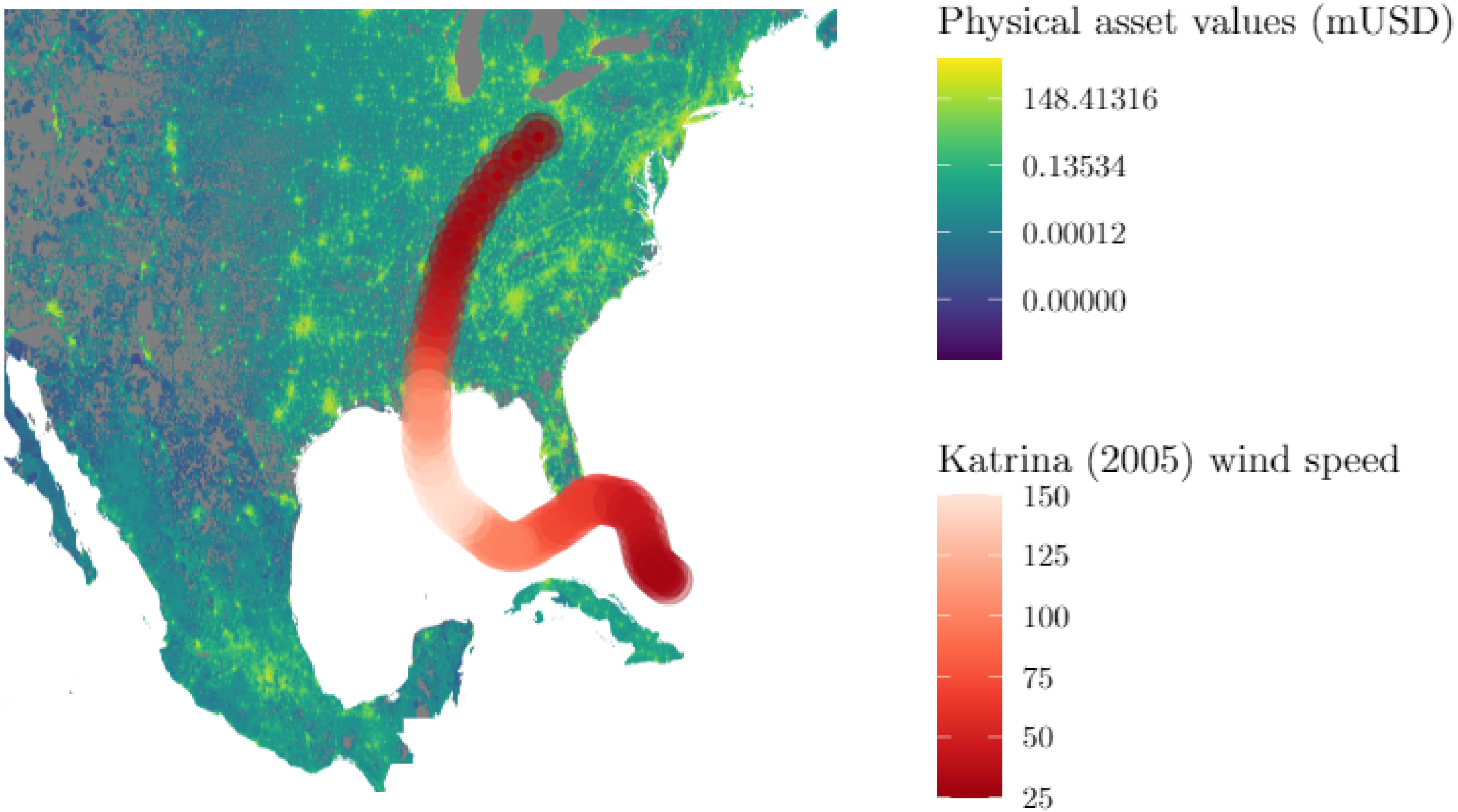



Source: Le Guenedal *et al.* (2021).

# Climate physical risk

## Tropical cyclone damage modeling

Figure 36: The case of Katrina (2005)

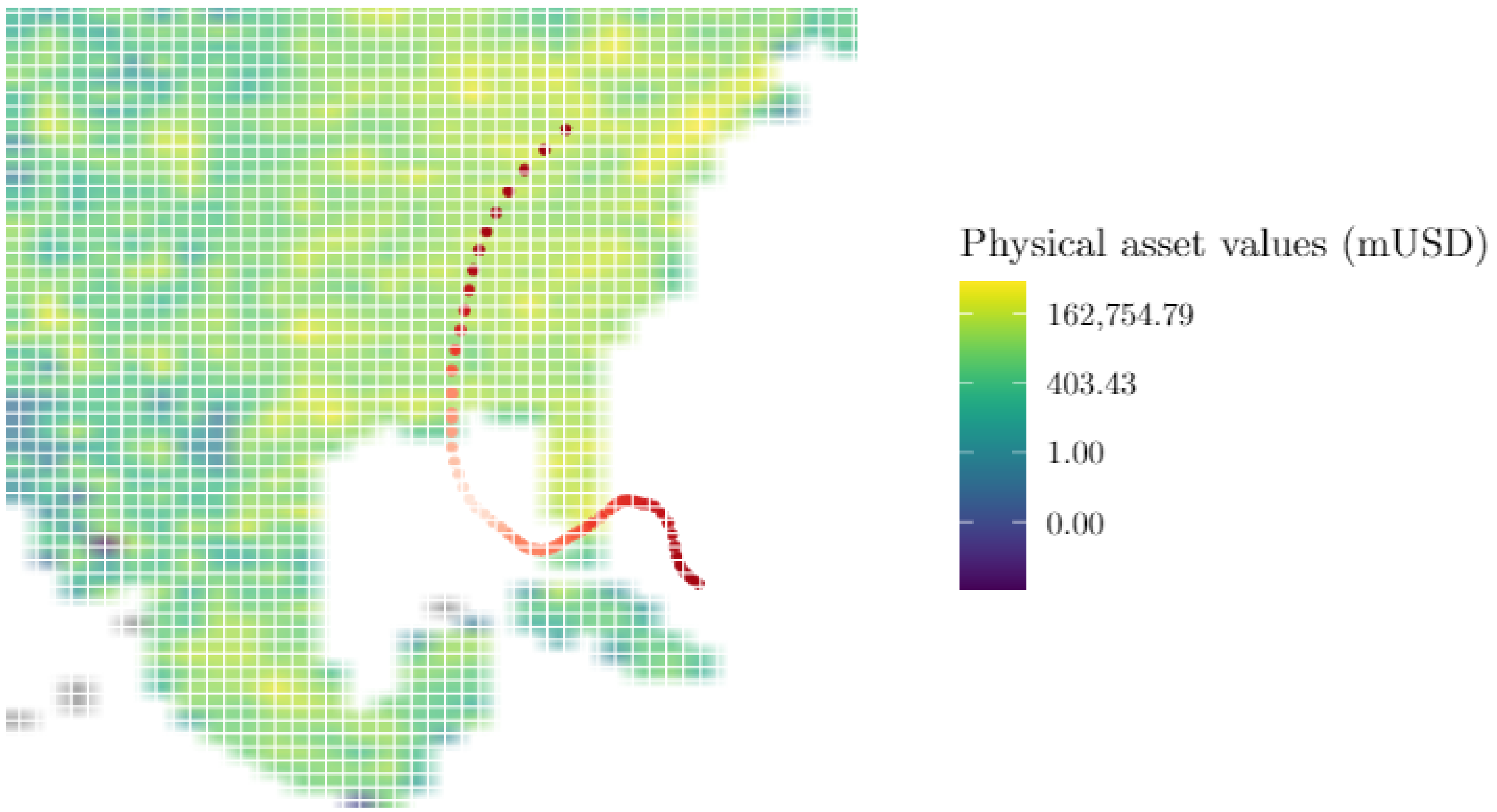



Source: Le Guenedal *et al.* (2021).

# Climate physical risk

## Tropical cyclone damage modeling

Figure 37: The grid approach

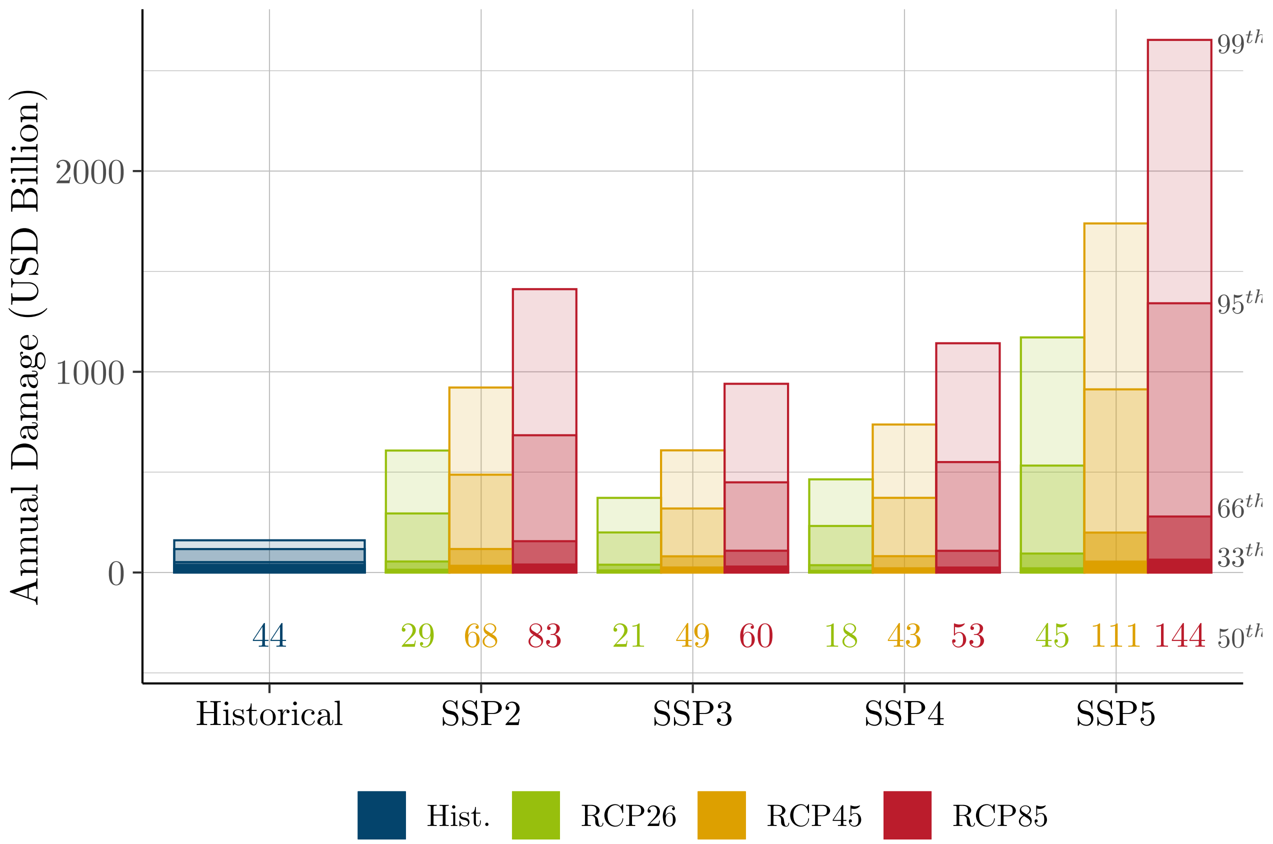



Source: Le Guenedal *et al.* (2021).

# Climate physical risk

## Tropical cyclone damage modeling

Figure 38: Average global losses




Source: Le Guenedal *et al.* (2021).

# Climate physical risk

## Tropical cyclone damage modeling

Table 13: Average increase of financial losses per year

| SSP | RCP 2.6 | RCP 4.5 | RCP 8.5 |
|---|---|---|---|
| SSP2 | +43% | +153% | +247% |
| SSP5 | +157% | +360% | +543% |

Source: Le Guenedal *et al.* (2021).

**Remark**

- There are simulations that lead to annual losses that easily exceed 2 or 3 trillion dollars per year
- 1 Katrina = \$180 billion in 2005

# Scoring

⇒ Application of ESG scoring systems to climate risk

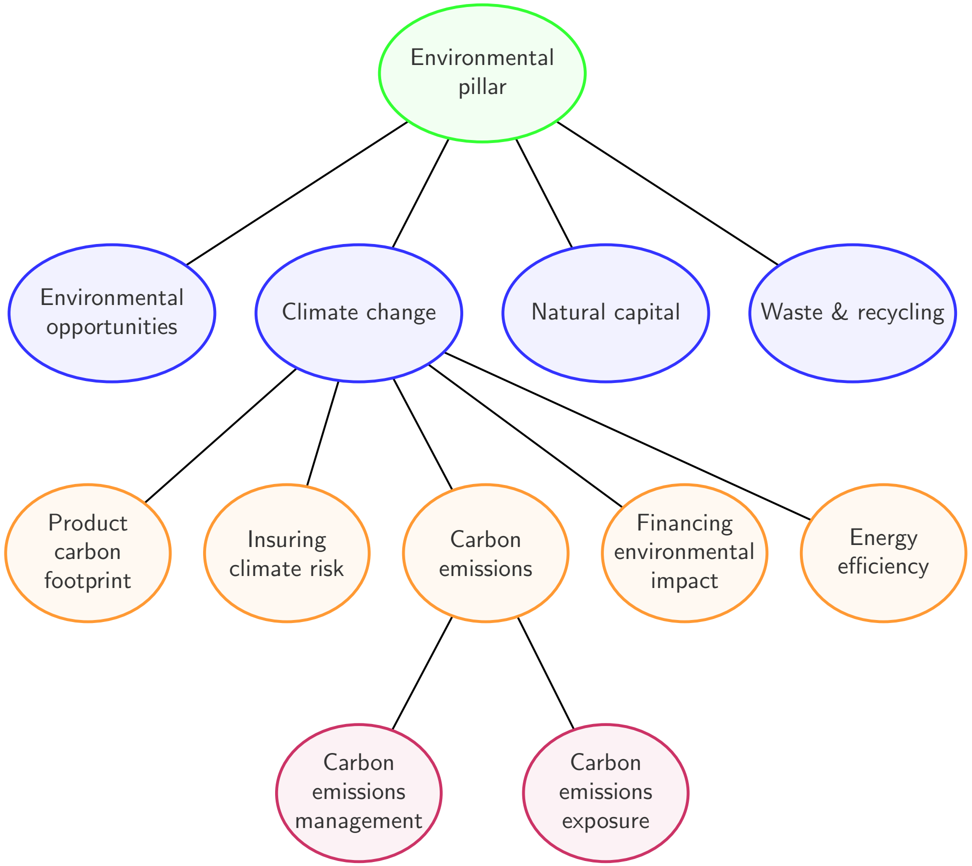



Figure 39: An example of E score

Source: MSCI (2020)

# Key performance indicators

- Avoided emissions
- Green revenues
- Energy mix
- Reserves-based indicators (capital stranding risk)
- Green patent, R&D and capital expenditure
- Etc.

Highly related to **Net Zero**

# Avoided emissions

- This metric compares the carbon emissions of a product or an issuer to a reference or benchmark
- For instance, a hybrid car emits[9] $CO_2$, but it also avoid carbon emissions compared to a petrol car
- The avoided emissions is defined as:

$$\mathcal{AE}_i = \sum_{k=1}^{n_p} \sum_{j=1}^{3} \left( \mathcal{CE}_j \left( k; \mathrm{reference} \right) - \mathcal{CE}_j \left( k; \mathrm{green} \right) \right)$$

where:

- $n_p$ is the products or services offered by the company $i$
- $\mathcal{CE}_j \left( k; \mathrm{green} \right)$ and $\mathcal{CE}_j \left( k; \mathrm{reference} \right)$ are the scope $j$ emissions of the green and reference products $k$

[9] Especially if we take into account the life cycle of batteries

# Avoided emissions

- There is no standards to compute avoided emissions
- World Resources Institute (2019), *Estimating and Reporting The Comparative Emissions Impacts of Products*, `https://ghgprotocol.org/estimating-and-reporting-avoided-emissions`
- Avoided emissions calculator: `https://www.irena.org/climatechange/Avoided-Emissions-Calculator`
- Avoided emissions depend on the sector, region, country, product, etc.
- Again, we notice a $\mathcal{SC}_{1+2}$ vs. $\mathcal{SC}_3$ puzzle $\Rightarrow$ the example of smartphones

# Green revenues

- The green revenues measure the share of the company's business in sustainable activities
- An issuer with 100% of green revenues is called a *pure player*
- Example of green revenues
  - Revenues from electric cars for the automobile sector
  - Renewable production (wind, solar, etc.) for the Utilities sector.

$\Rightarrow$ Extension to green CAPEX or OPEX

# Green revenues

**Green revenues**

1. Renewable energy
2. Direct contribution to the low-carbon transition
3. Indirect contribution to the low-carbon transition

**Brown revenues**

1. Coal mining
2. Oil & gas revenues
3. Activities using coal, oil & gas?

We need a **taxonomy** = **What is Green?**

By sector? activities? products?

# Taxonomy

## European Taxonomy (EUT)

There are 6 objectives:

1. Climate change mitigation
2. Climate change adaptation
3. Sustainable and protection of water and marine resources
4. Transition to a circular economy
5. Pollution prevention and control
6. Protection and restoration of biodiversity and ecosystem

# Taxonomy

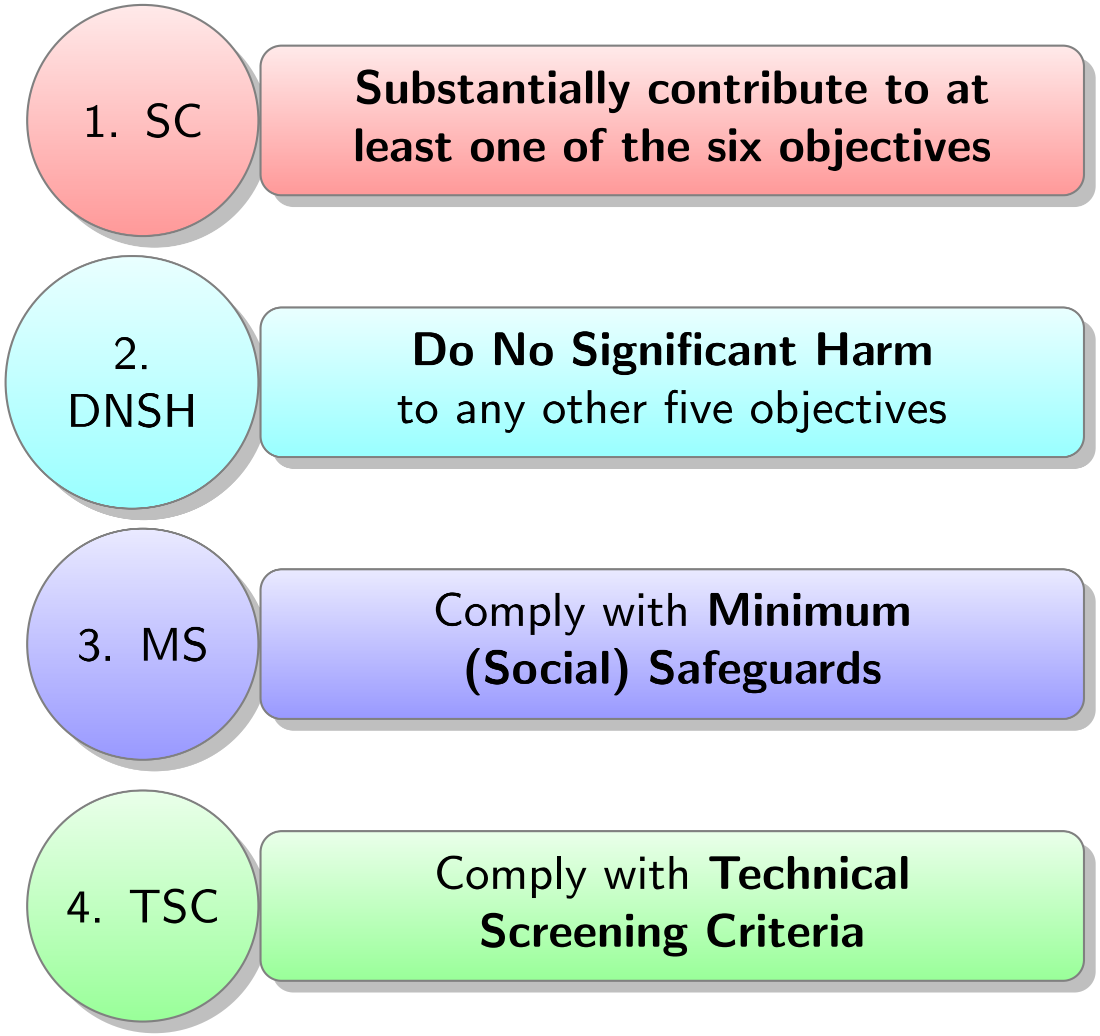



Figure 40: EU taxonomy

# Taxonomy

## Activities

1. Low carbon activities (or "**green**" activities)
   Activities associated with sequestration or very low absolute emissions
2. Transition activities (or "**greening of**" activities)
   Activities that contribute to a transition to a net zero emissions economy in 2050 but are not currently close to a net zero carbon emissions level
3. Enabling activities (or "**greening by**" activities)
   Activities that enable low-carbon performance or enable substantial emissions reductions (life-cycle considerations)

## Controversies

- Gas
- Nuclear

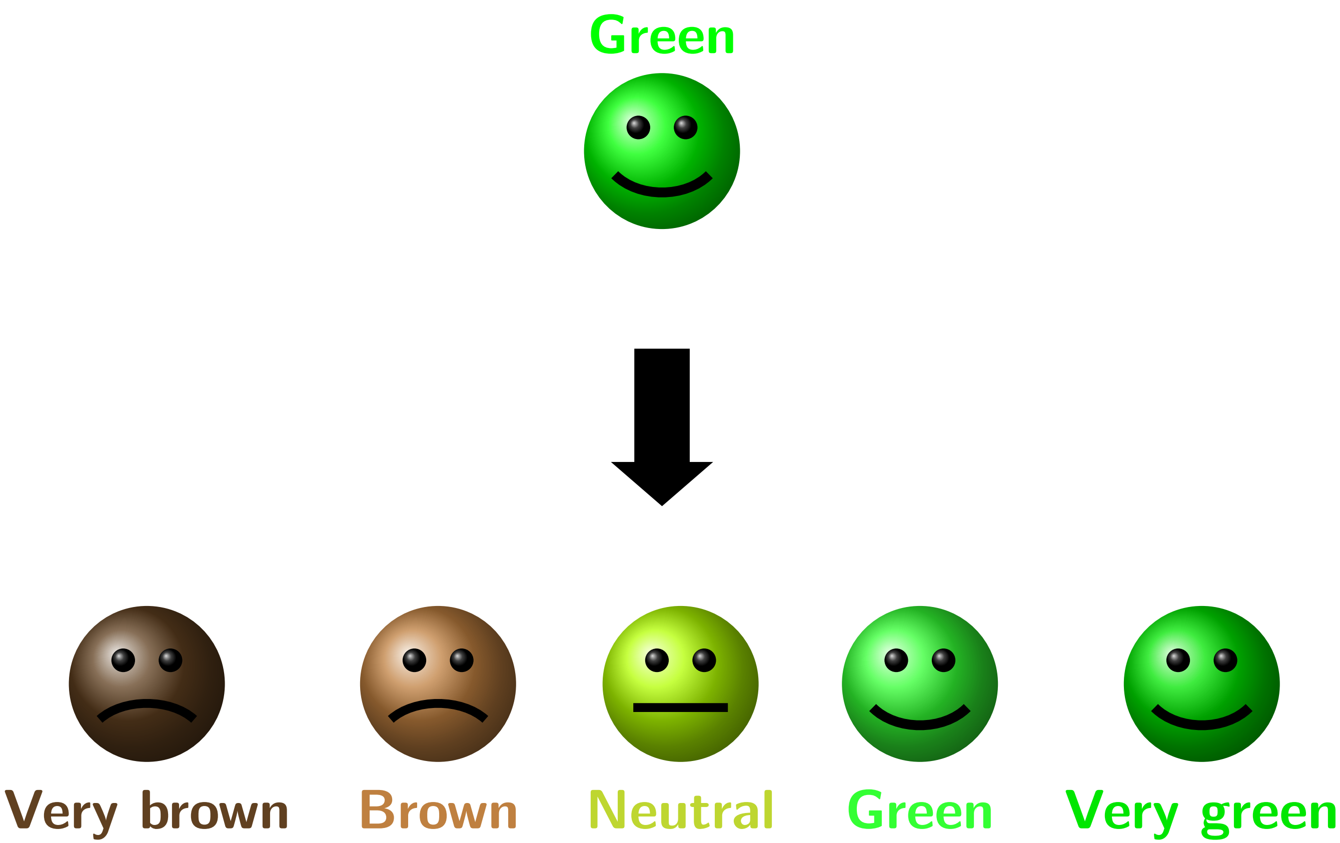
# Taxonomy

The EU taxonomy leads to a narrow definition of **GREEN**:

- It generally concerns less than 5% of the allocation of cap-weighted indices
- It is difficult to commit on EU taxonomy alignment, except for thematics (green bonds, cleantech, etc.)
- The most represented sectors are: softwares & services, semiconductors, real estate, automobiles, capital goods, materials & utilities
- Some sectors are not in the EU taxonomy: banks, food, health care, insurance, media, retailing
- Sector biases are incompatible with portfolio diversification

# Taxonomy

**What we need**

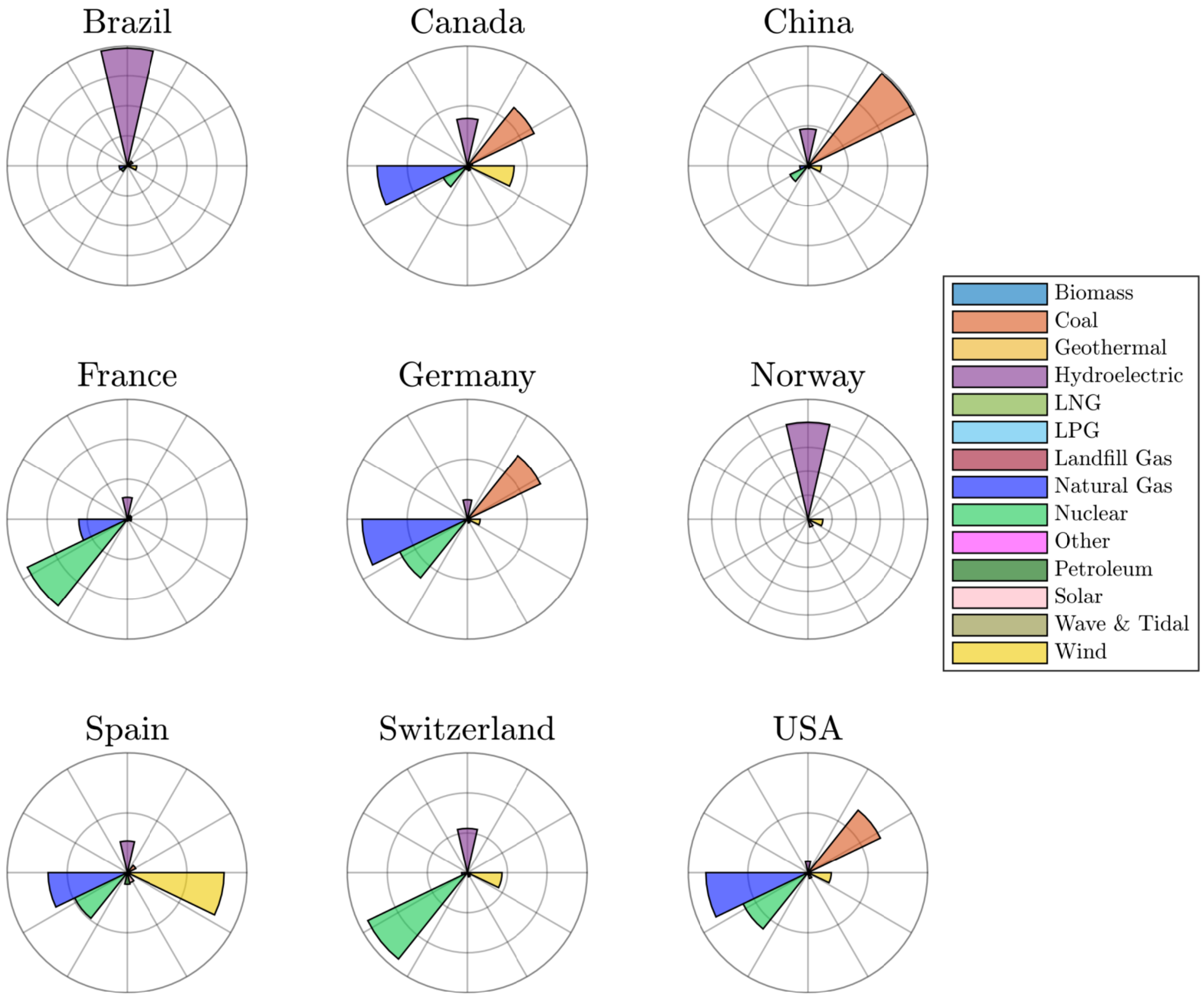


# Energy mix

- How to measure the environmental performance of a Utility company?
- How to measure the environmental performance of a country?
- How to compare a company located in a country with a bad enery meix

# Bottom up energy mix$^{(*)}$ (in %)

This figure presents the energy generation breakdown for some countries. We can distinguish countries that rely on hydroelectric power (Brazil, Norway), nuclear (France, Switzerland) and mixed solutions (Canada, Germany, Spain, USA)




$^{(*)}$ Each grid circle represents 20% of energy generation. The scale of the radar chart is then 40% for Canada, Germany, Spain and USA, 60% for China, France and Switzerland, 80% for Brazil and 100% for Norway