Course 2022-2023 in Sustainable Finance
Lecture 7. Economic Modeling of Climate Change

Thierry Roncalli*

*Amundi Asset Management[1]

*University of Paris-Saclay

March 2023

[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.

Sustainable growth and climate change

"*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

Sustainable growth and climate change

Environmental — Economy

Social — Sustainability

Gouvernance — Growth

Adam Smith (1776)

An Inquiry into the Nature and Causes of The Wealth of Nations

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, δ_K is the depreciation rate of capital and g_A and g_L are the productivity and labor growth rates

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).

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

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 δ_{N_c} is the depreciation rate of natural capital and ϑ 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

Inter-temporal utility functions

Preferences modeling (Ramsey model)

- ρ 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 θ is the risk aversion parameter
- Maximization of the welfare function:

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

The discounting issue

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

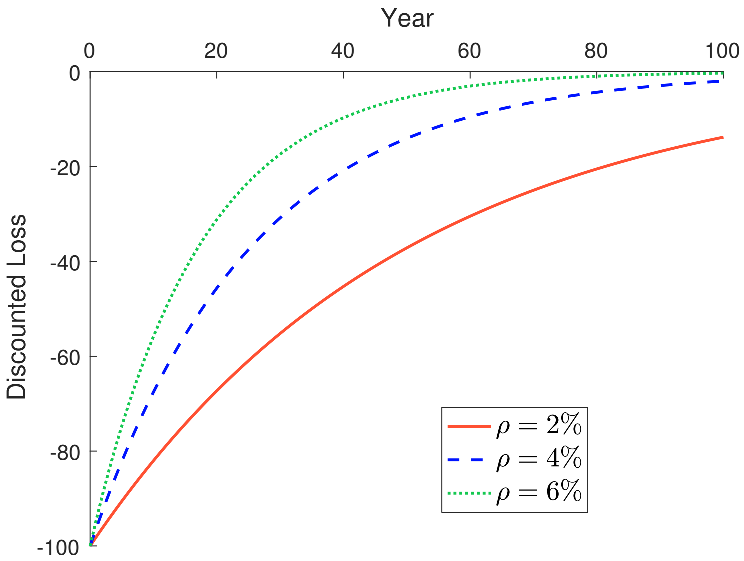


Figure 1: Discounted value of $100 loss

- "*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!

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

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 models (IAMs)

Main categories

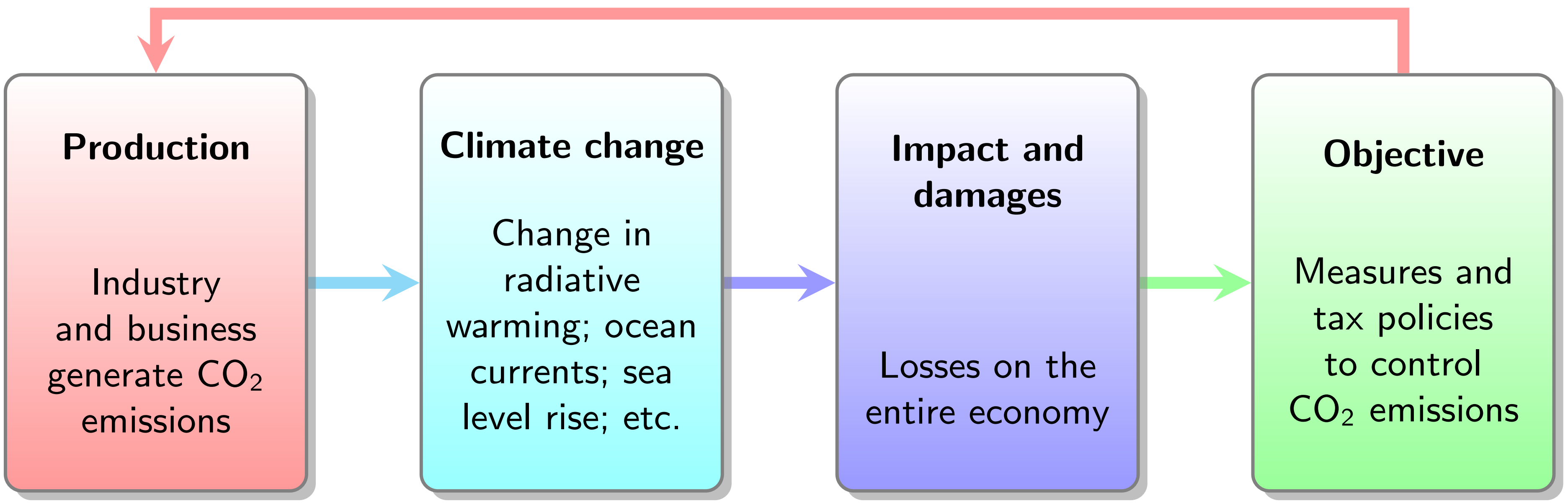
- **Optimization models**
  The inputs of these models are parameters and assumptions about the structure of the relationships between variables. The outputs provided by optimization process are scenarios depending on a set of constraints
- **Evaluation models**
  Based on exogenous scenarios, the outputs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

Three main components of IAMs

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

Modeling framework

Figure 2: Economic models of climate risk



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

Modeling framework

The most famous IAM is the **Dynamic Integrated model of Climate and the Economy** (or DICE) developed by William Nordhaus[2]

[2] 2018 Nobel Laureate

Economic module

Production and consumption functions

- The **gross production** $Y(t)$ is given by a Cobb-Douglas function:

$$Y(t) = A(t) K(t)^{\gamma} L(t)^{1-\gamma}$$

  where:
  - $A(t)$ is the total productivity factor
  - $K(t)$ is the capital input
  - $L(t)$ is the labor input
  - $\gamma \in]0,1[$ measures the elasticity of the capital factor:
- Climate change impacts the **net output**:

$$Q(t) = \Omega_{\text{climate}}(t) Y(t) \leq Y(t)$$

- Classical identities $Q(t) = C(t) + I(t)$ and $I(t) = s(t) Q(t)$

Economic module

Production and consumption functions

- The dynamics of the state variables are:

$$\left\{\begin{array}{l} A(t) = (1 + g_A(t)) A(t-1) \\ K(t) = (1 - \delta_K) K(t-1) + I(t) \\ L(t) = (1 + g_L(t)) L(t-1) \end{array}\right.$$

- We have:

$$\left\{\begin{array}{l} g_A(t) = \dfrac{1}{1 + \delta_A} g_A(t-1) \\ g_L(t) = \dfrac{1}{1 + \delta_L} g_L(t-1) \end{array}\right.$$

Economic module
Labor input

Example #1

The world population was equal to 7.725 billion in 2019 and 7.805 billion in 2020. At the beginning of the 1970s, we estimate that the annual growth rate was equal to 2.045%. According to the United Nations, the global population could surpass 10 billion by 2100.

Economic module

Labor input

- In 2020, the annual growth rate was equal to:

$$g_L(2020) = \frac{L(2020)}{L(2019)} - 1 = \frac{7.805}{7.725} - 1 = 1.036\%$$

- Since we have $g_L(t) = \left(\frac{1}{1+\delta_L}\right)^{t-t_0} g_L(t_0)$, we deduce that:

$$\delta_L = \left(\frac{g_L(t_0)}{g_L(t)}\right)^{1/(t-t_0)} - 1$$

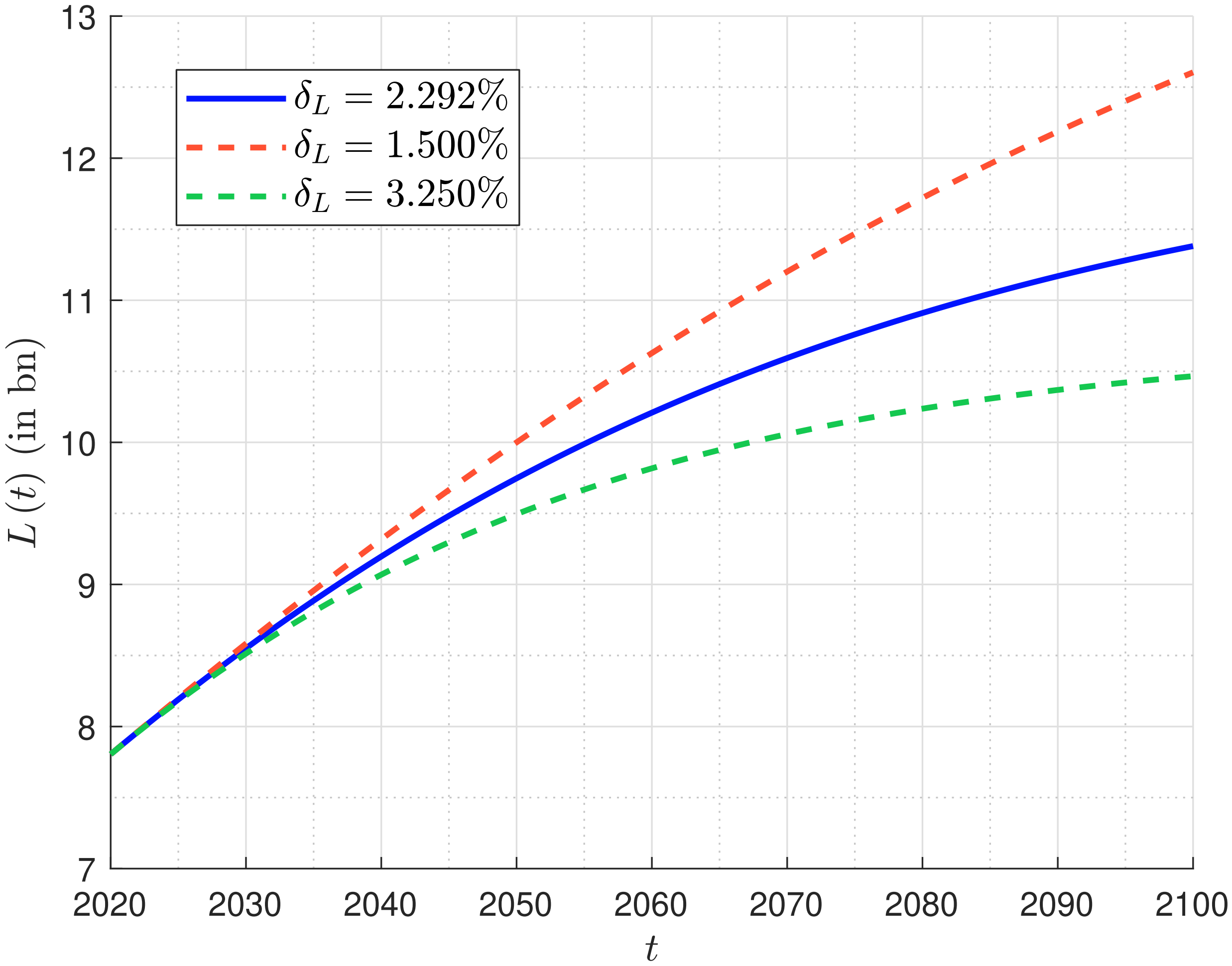
- An estimate of δ_L is then:

$$\delta_L = \left(\frac{g_L(1970)}{g_L(2020)}\right)^{1/30} - 1 = 2.292\%$$

Economic module

Labor input

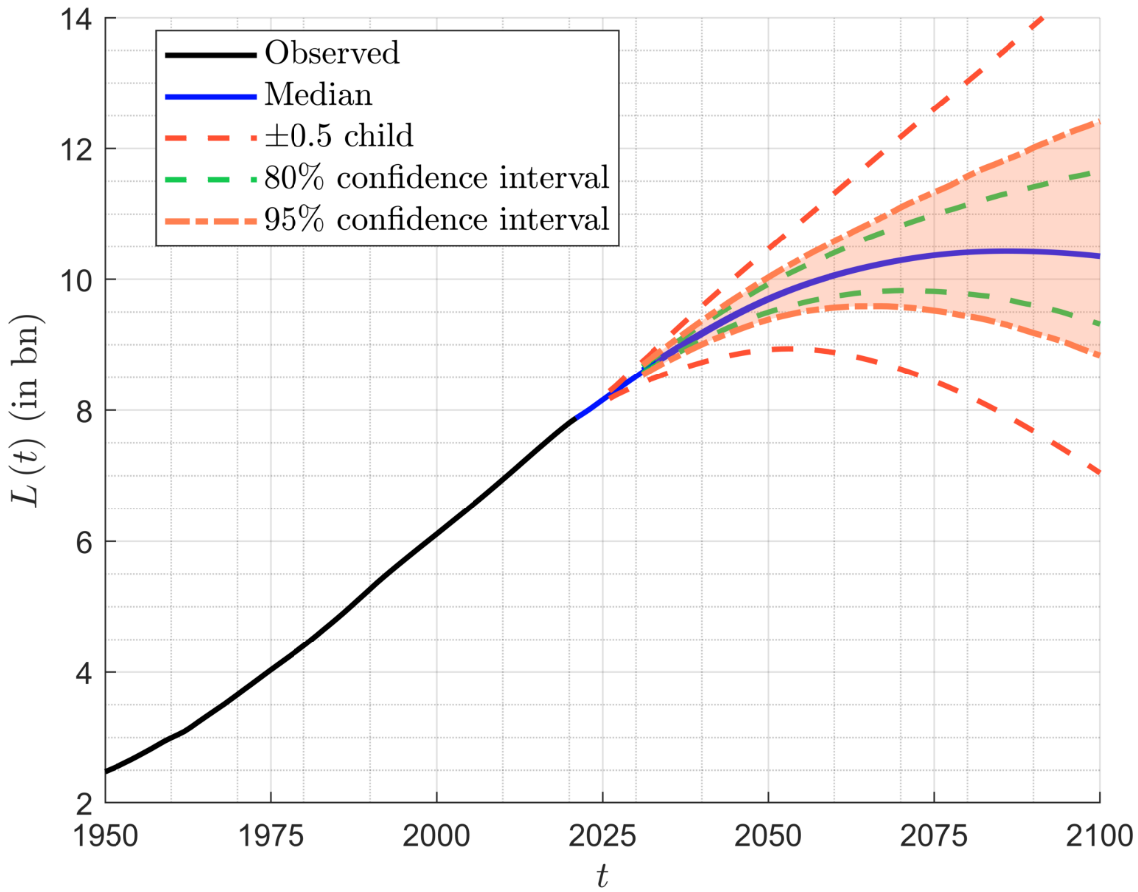
Figure 3: Evolution of the labor input $L(t)$



Economic module

Labor input

Figure 4: Projection of the world population



Source: United Nations (2022), `https://population.un.org/wpp`.

Economic module

Labor input

- AR(1) model:

$$g_L(t) = \phi g_L(t-1) + \varepsilon(t)$$

We have

$$\hat{\delta}_L = \frac{\left(1 - \hat{\phi}\right)}{\hat{\phi}}$$

- Log-linear model:

$$\ln g_L(t) = \beta_0 + \beta_1 (t - t_0) + \varepsilon(t)$$

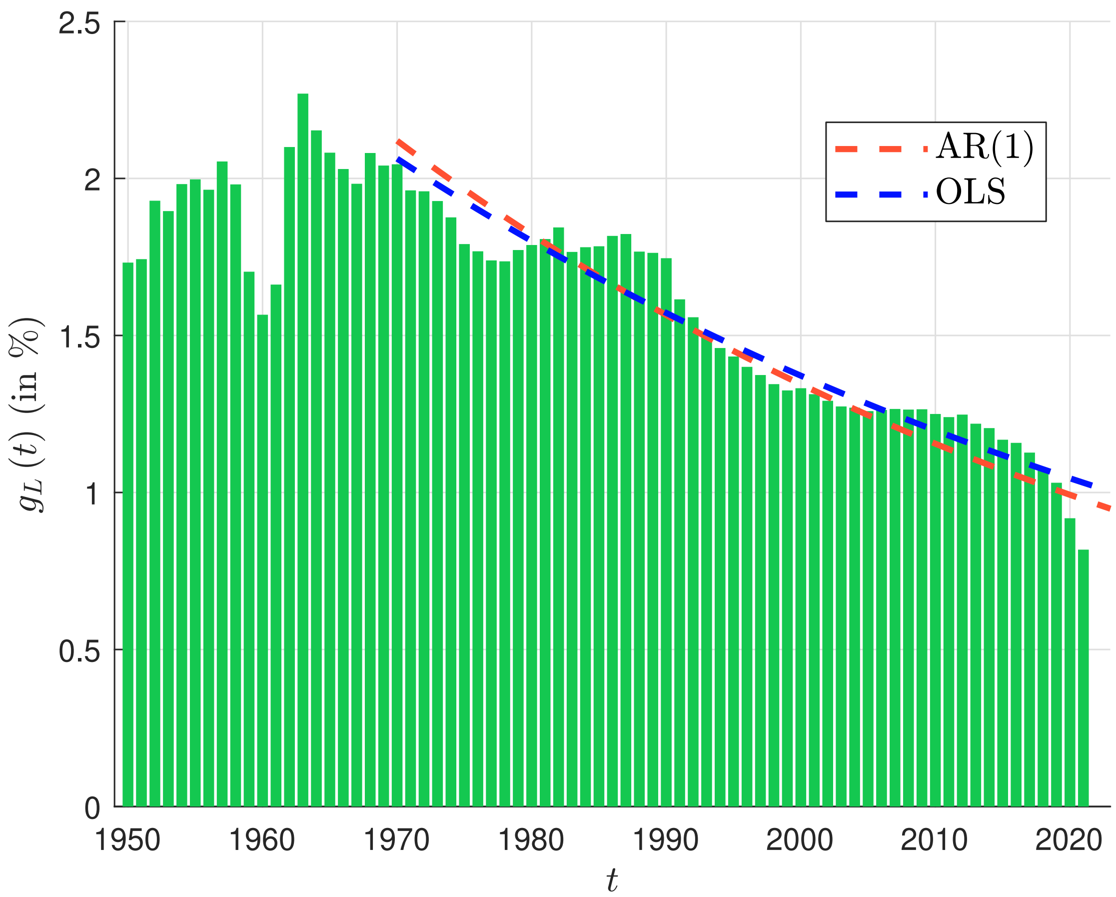
We have:

$$\hat{\delta}_L = e^{-\hat{\beta}_1} - 1$$

Economic module

Labor input

Figure 5: Population growth rate



Source: United Nations (2022), `https://population.un.org/wpp` & Author's calculations.

Economic module

Total factor productivity

Table 1: Average productivity growth rate (in %)

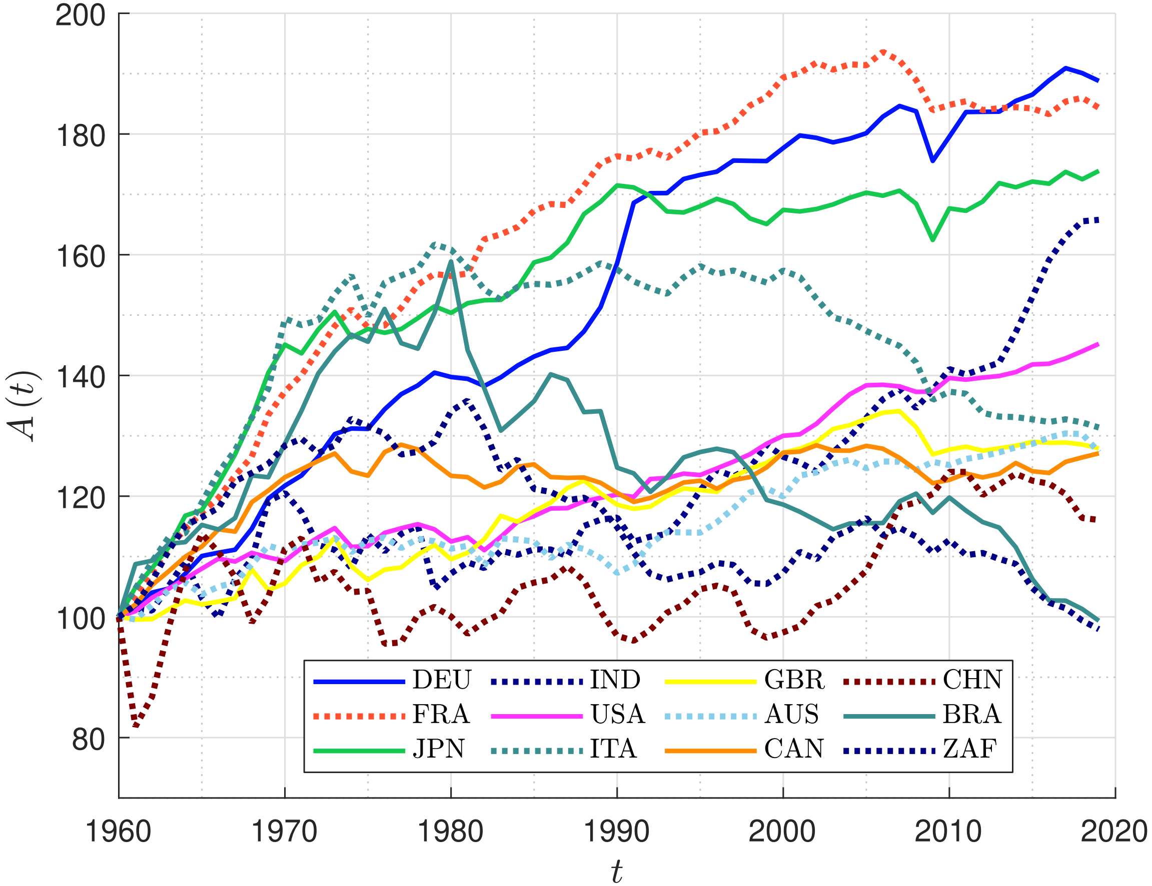
Country	1960-1970	1970-1980	1980-1990	1990-2000	2000-2010	2010-2020
AUS	1.02	0.07	−0.23	1.02	0.36	0.13
BRA	2.39	2.05	−1.04	−1.12	−0.17	−1.63
CAN	2.18	0.38	−0.25	0.21	−0.21	0.40
CHN	−0.03	−0.06	−0.04	−0.41	2.24	−0.35
FRA	3.59	1.63	1.12	0.61	−0.11	0.02
DEU	2.33	1.63	0.75	1.52	0.01	0.74
IND	2.37	−1.22	1.06	1.04	0.70	1.89
ITA	3.71	1.66	−0.19	−0.20	−1.32	−0.34
JPN	4.05	0.77	1.09	−0.22	−0.15	0.69
ZAF	2.37	0.30	−0.84	−1.11	0.50	−1.20
GBR	0.50	0.72	0.75	0.42	0.12	0.08
USA	1.00	0.42	0.46	0.73	0.65	0.56

Source: Penn World Table 10.01 (Feenstra *et al.*, 2015) & Author's calculations.

Economic module

Total factor productivity

Figure 6: Total factor productivity index (base 100 = 1960)

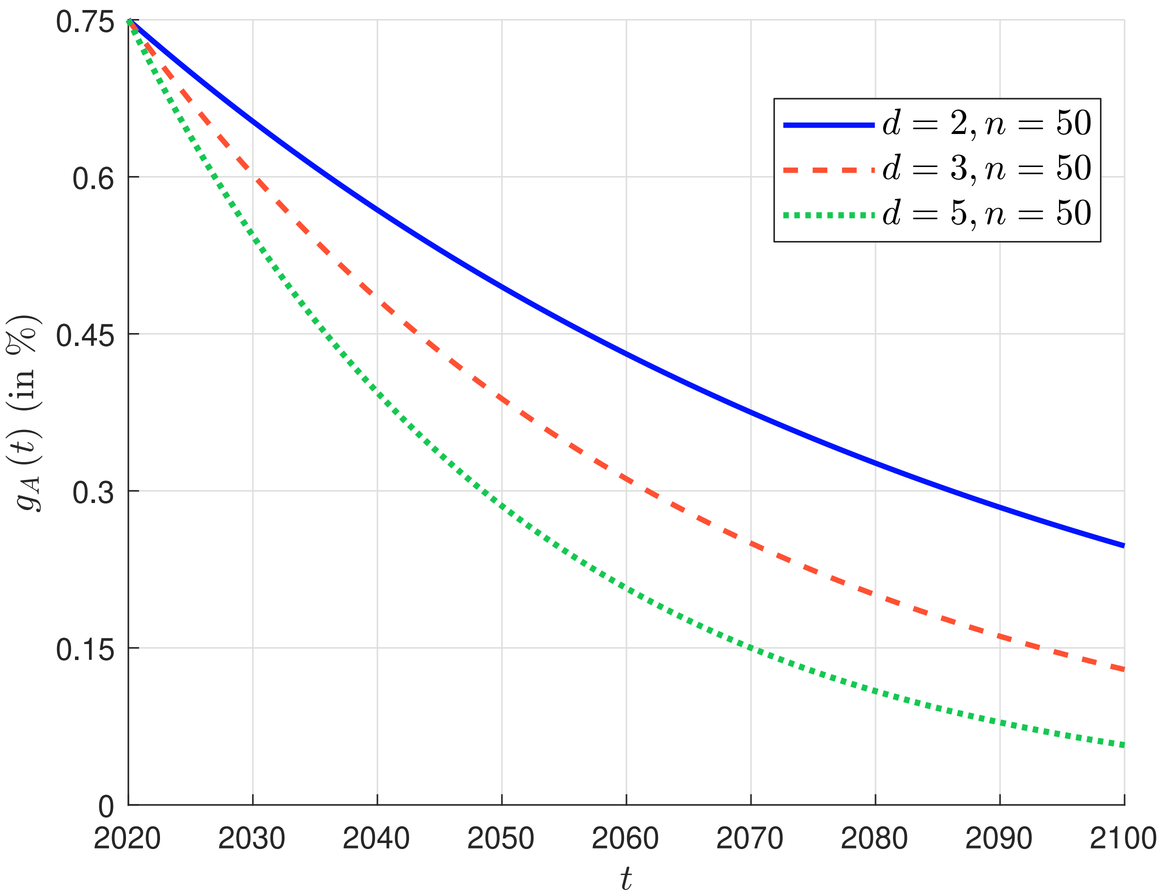


Source: Penn World Table 10.01 (Feenstra *et al.*, 2015) & Author's calculations.

Economic module

Total factor productivity

Figure 7: Dynamics of the TFP growth rate*



*We use the following calibration rule: $\delta_A = \sqrt[n]{d} - 1$

Economic module

Investment, capital stock and gross output

- Penn World Table/IMF's ICSD
- In 2019, we obtain $I(2019) = \$30.625$ tn, $K(2019) = \$318.773$ tn and $Y(2019) = \$124.418$ tn
- We also have:

$$\delta_K(t) = \frac{K(t-1) - K(t) + I(t)}{K(t-1)}$$

  and we obtain $\delta_K(2019) = 6.25\%$
- To calibrate the initial value of $A(t)$, we inverse the Coob-Douglas function:

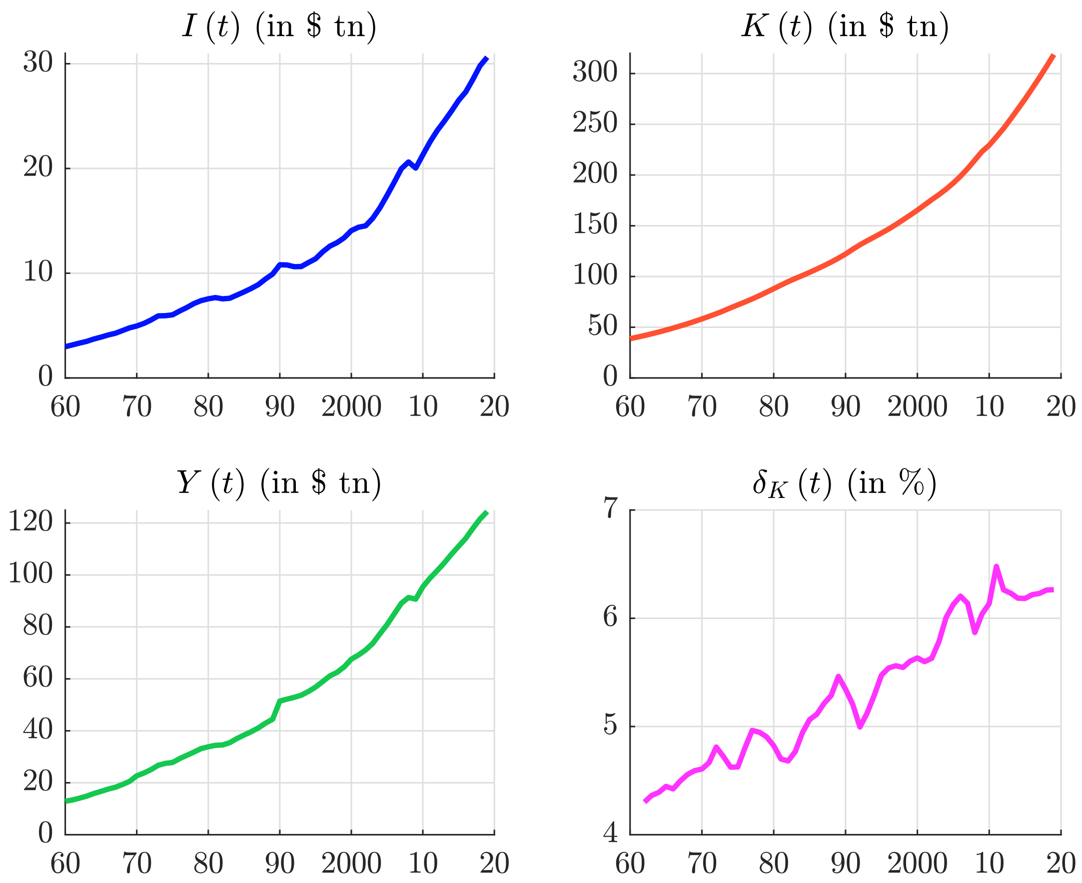
$$A(2019) = \frac{Y(t)}{K(t)^{\gamma} L(t)^{1-\gamma}} = \frac{124.418}{318.773^{0.30} \times 7.725^{0.70}} = 5.276$$

- The saving rate $s(t)$ is exogenous

Economic module

Investment, capital stock and gross output

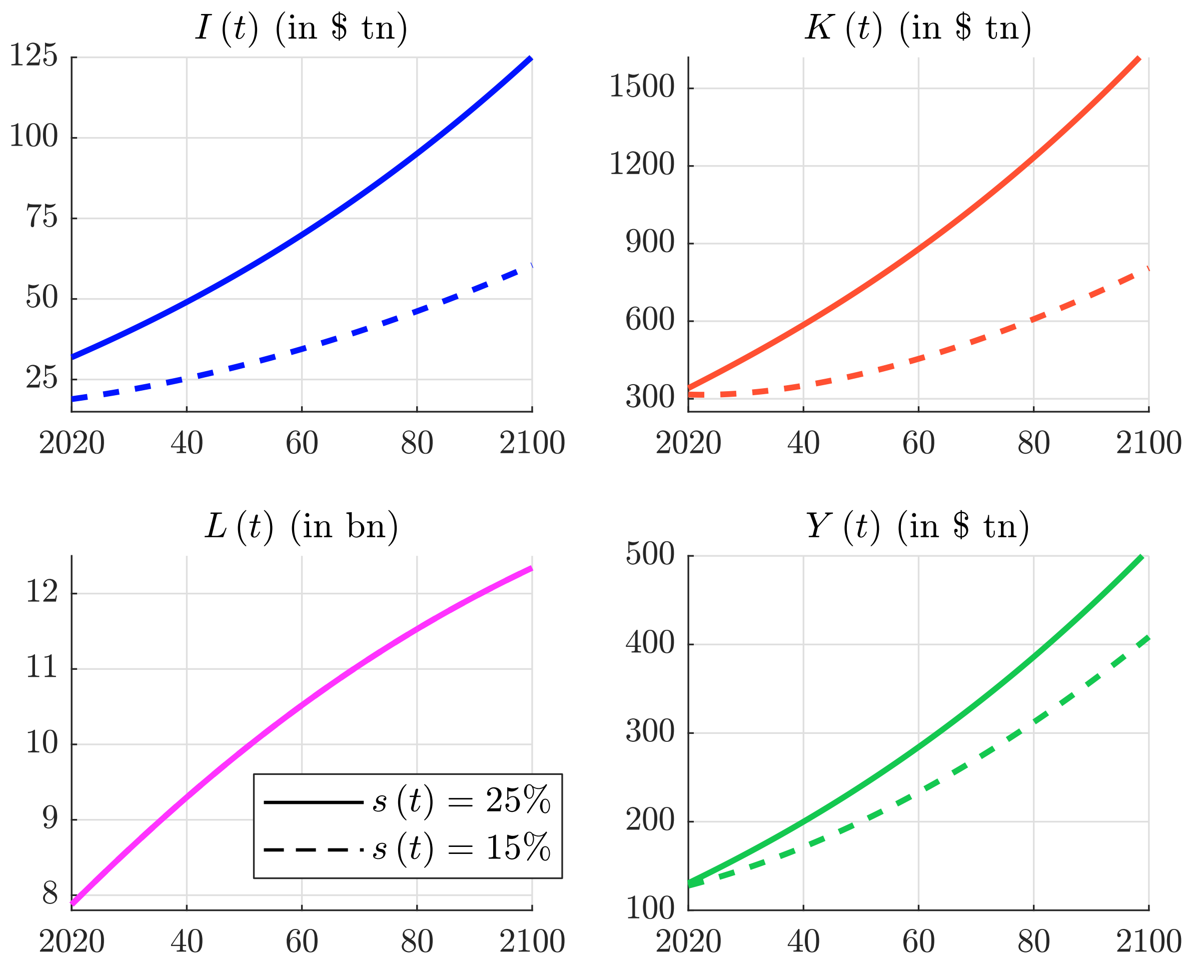
Figure 8: Historical estimates of $I(t)$, $K(t)$, $Y(t)$ and $\delta_K(t)$



Source: IMF Investment and Capital Stock Dataset (2021) & Author's calculations.

Economic module

Figure 9: Simulation of the DICE macroeconomic module



Economic module

Cost function of climate change

- The survival function is given by:

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

where:

  - $D(t) \geq 0$ is the climate damage function (physical risk)
  - $\Lambda(t) \geq 0$ is the mitigation or abatement cost (transition risk)

Economic module

Cost function of climate change

- The cost $D(t)$ resulting from natural disasters depends on the atmospheric temperature $\mathcal{T}_{\mathrm{AT}}(t)$:

$$D(t) = \psi_1 \mathcal{T}_{\mathrm{AT}}(t) + \psi_2 \mathcal{T}_{\mathrm{AT}}(t)^2$$

- The abatement cost function depends on the control variable $\mu(t)$:

$$\Lambda(t) = \theta_1(t) \mu(t)^{\theta_2}$$

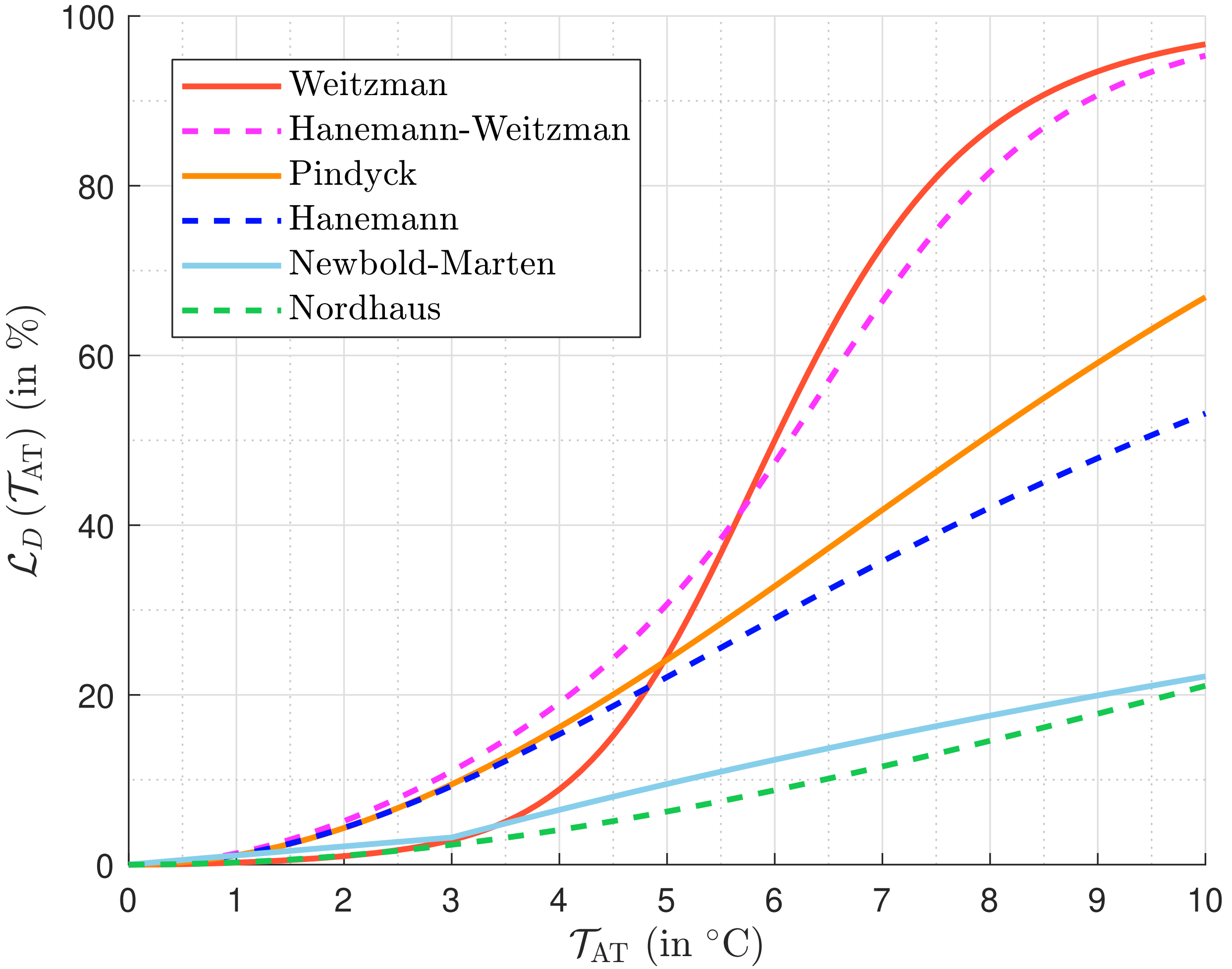
- The global impact of climate change is equal to:

$$\Omega_{\mathrm{climate}}(t) = \frac{1 - \theta_1(t) \mu(t)^{\theta_2}}{1 + \psi_1 \mathcal{T}_{\mathrm{AT}}(t) + \psi_2 \mathcal{T}_{\mathrm{AT}}(t)^2}$$

Economic module

Cost function of climate change

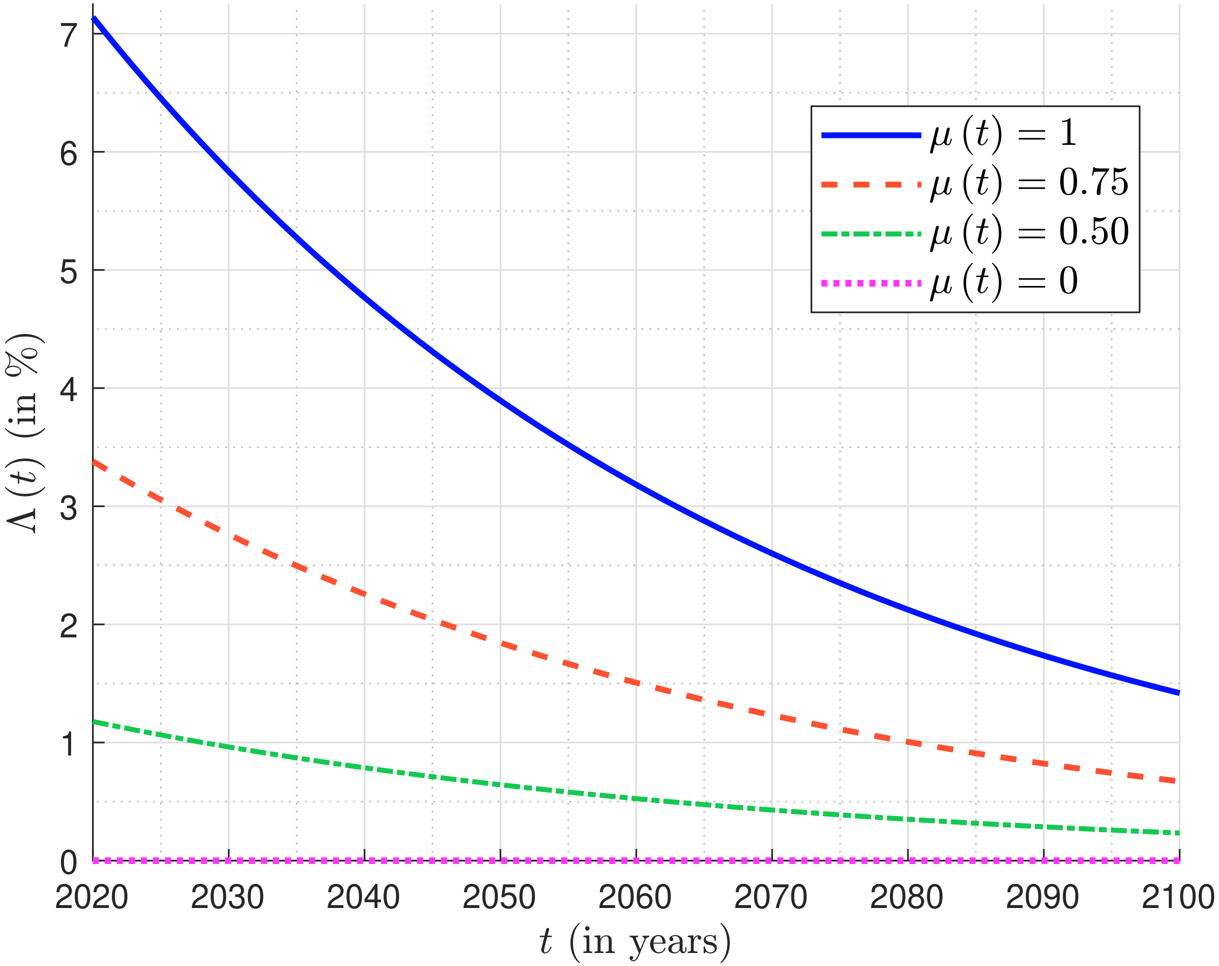
Figure 10: Loss function due to climate damage costs



Economic module

Cost function of climate change

Figure 11: Abatement cost function



Climate module
GHG emissions

- The total GHG emissions depends on the production $Y(t)$ and the land use emissions $\mathcal{CE}_{\text{Land}}(t)$:

$$\begin{aligned}\mathcal{CE}(t) &= \mathcal{CE}_{\text{Industry}}(t) + \mathcal{CE}_{\text{Land}}(t) \\ &= (1 - \mu(t))\sigma(t) Y(t) + \mathcal{CE}_{\text{Land}}(t)\end{aligned}$$

- $\sigma(t)$ is the anthropogenic carbon intensity of the economy:

$$\sigma(t) = (1 + g_\sigma(t))\sigma(t-1)$$

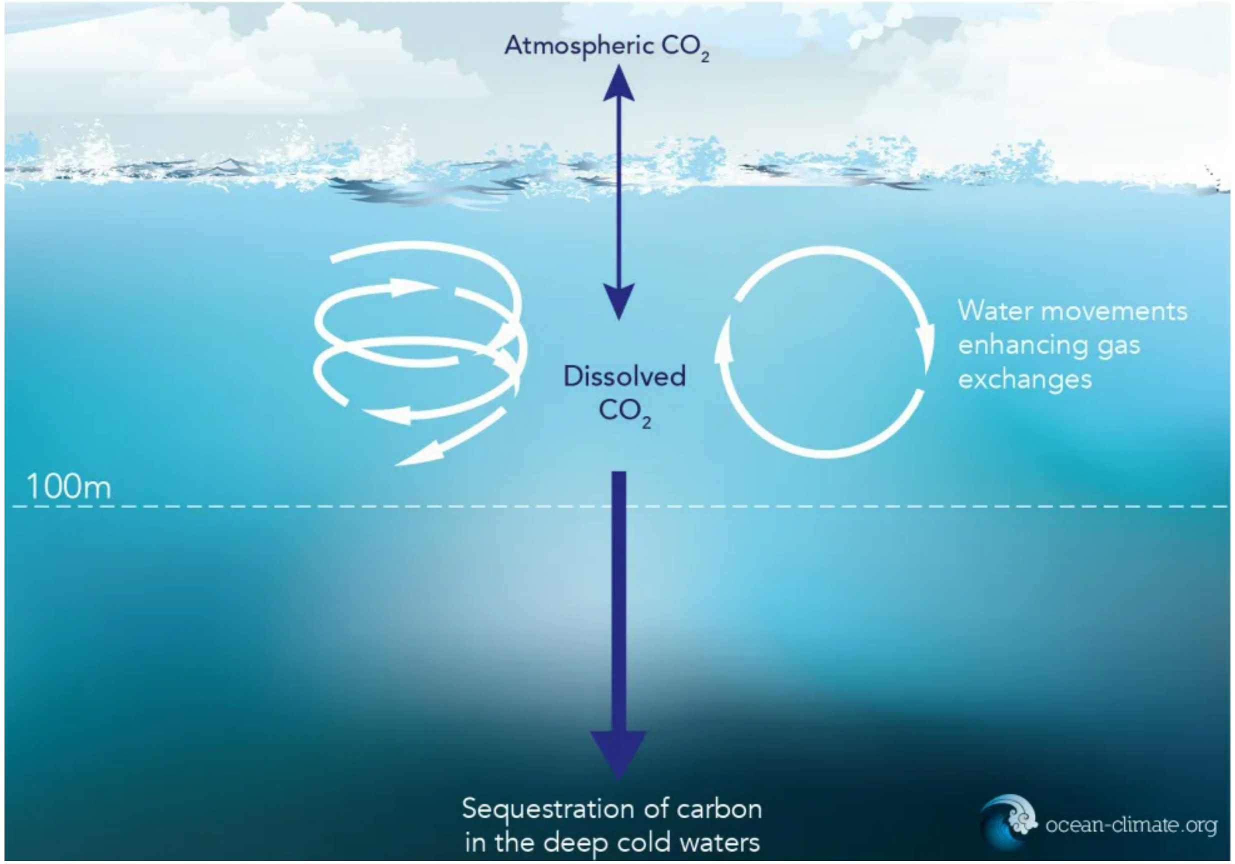
where:

$$g_\sigma(t) = \frac{1}{1 + \delta_\sigma} g_\sigma(t-1)$$

Climate module

Temperature modeling

Figure 12: Physical carbon pump



Source: `ocean-climate.org`.

Climate module

Concentration modeling

- We have:

$$\left\{\begin{array}{l} \mathcal{CC}_{\mathrm{AT}}(t) = \phi_{1,1}\mathcal{CC}_{\mathrm{AT}}(t-1) + \phi_{1,2}\mathcal{CC}_{\mathrm{UP}}(t-1) + \phi_{1}\boldsymbol{\mathcal{CE}}(t) \\ \mathcal{CC}_{\mathrm{UP}}(t) = \phi_{2,1}\mathcal{CC}_{\mathrm{AT}}(t-1) + \phi_{2,2}\mathcal{CC}_{\mathrm{UP}}(t-1) + \phi_{2,3}\mathcal{CC}_{\mathrm{LO}}(t-1) \\ \mathcal{CC}_{\mathrm{LO}}(t) = \phi_{3,2}\mathcal{CC}_{\mathrm{UP}}(t-1) + \phi_{3,3}\mathcal{CC}_{\mathrm{LO}}(t-1) \end{array}\right.$$

- The dynamics of $\mathcal{CC} = (\mathcal{CC}_{\mathrm{AT}}, \mathcal{CC}_{\mathrm{UP}}, \mathcal{CC}_{\mathrm{LO}})$ is a VAR(1) process:

$$\mathcal{CC}(t) = \Phi_{\mathcal{CC}}\mathcal{CC}(t-1) + B_{\mathcal{CC}}\boldsymbol{\mathcal{CE}}(t)$$

Carbon cycle diffusion matrix

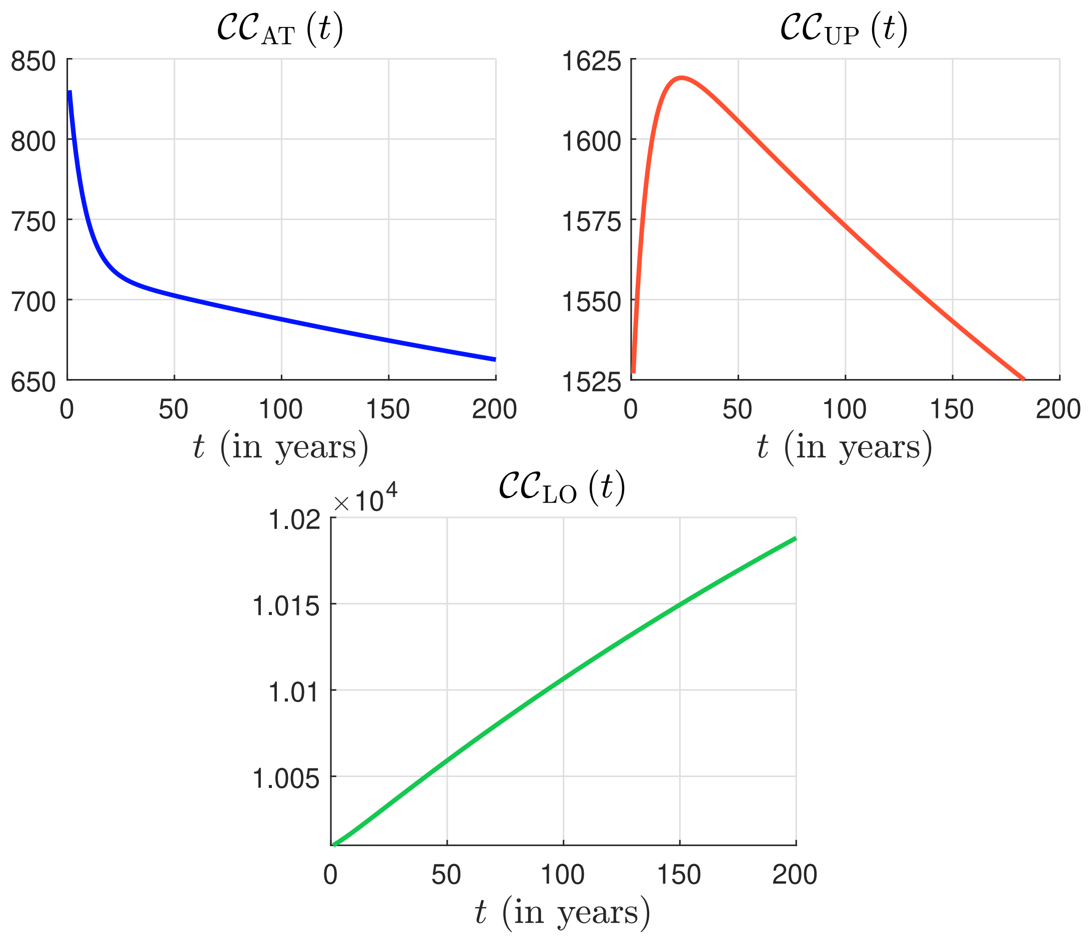
We have:

$$\Phi_{\mathcal{CC}} = \begin{pmatrix} 91.20\% & 3.83\% & 0 \\ 8.80\% & 95.92\% & 0.03\% \\ 0 & 0.25\% & 99.97\% \end{pmatrix}$$

Climate module

Concentration modeling

Figure 13: Impulse response analysis ($\Delta\mathcal{CE} = -1$ GtCO$_2$e)



Climate module

Radiative forcing

We have:

$$\mathcal{F}_{\mathrm{RAD}}(t) = \frac{\eta}{\ln 2} \ln \left(\frac{\mathcal{CC}_{\mathrm{AT}}(t)}{\mathcal{CC}_{\mathrm{AT}}(1750)} \right) + \mathcal{F}_{\mathrm{EX}}(t)$$

where:

- $\mathcal{F}_{\mathrm{RAD}}(t)$ is the change in total radiative forcing of GHG emissions since 1750 (expressed in $\mathrm{W/m^2}$)
- η is the temperature forcing parameter
- $\mathcal{F}_{\mathrm{EX}}(t)$ is the exogenous forcing (other GHG emissions)

Climate module

Temperature modeling

- The climate system for temperatures is characterized by a two-layer system:

$$\left\{ \begin{array}{lcl} \mathcal{T}_{\mathrm{AT}}(t) & = & \mathcal{T}_{\mathrm{AT}}(t-1) + \xi_1 \left(\mathcal{F}_{\mathrm{RAD}}(t) - \xi_2 \mathcal{T}_{\mathrm{AT}}(t-1) - \right. \\ & & \left. \xi_3 \left(\mathcal{T}_{\mathrm{AT}}(t-1) - \mathcal{T}_{\mathrm{LO}}(t-1) \right) \right) \\ \mathcal{T}_{\mathrm{LO}}(t) & = & \mathcal{T}_{\mathrm{LO}}(t-1) + \xi_4 \left(\mathcal{T}_{\mathrm{AT}}(t-1) - \mathcal{T}_{\mathrm{LO}}(t-1) \right) \end{array} \right.$$

- Let $\mathcal{T} = (\mathcal{T}_{\mathrm{AT}}, \mathcal{T}_{\mathrm{LO}})$ be the temperature vector. We have:

$$\mathcal{T}(t) = \Xi_{\mathcal{T}} \mathcal{T}(t-1) + B_{\mathcal{T}} \mathcal{F}_{\mathrm{RAD}}(t)$$

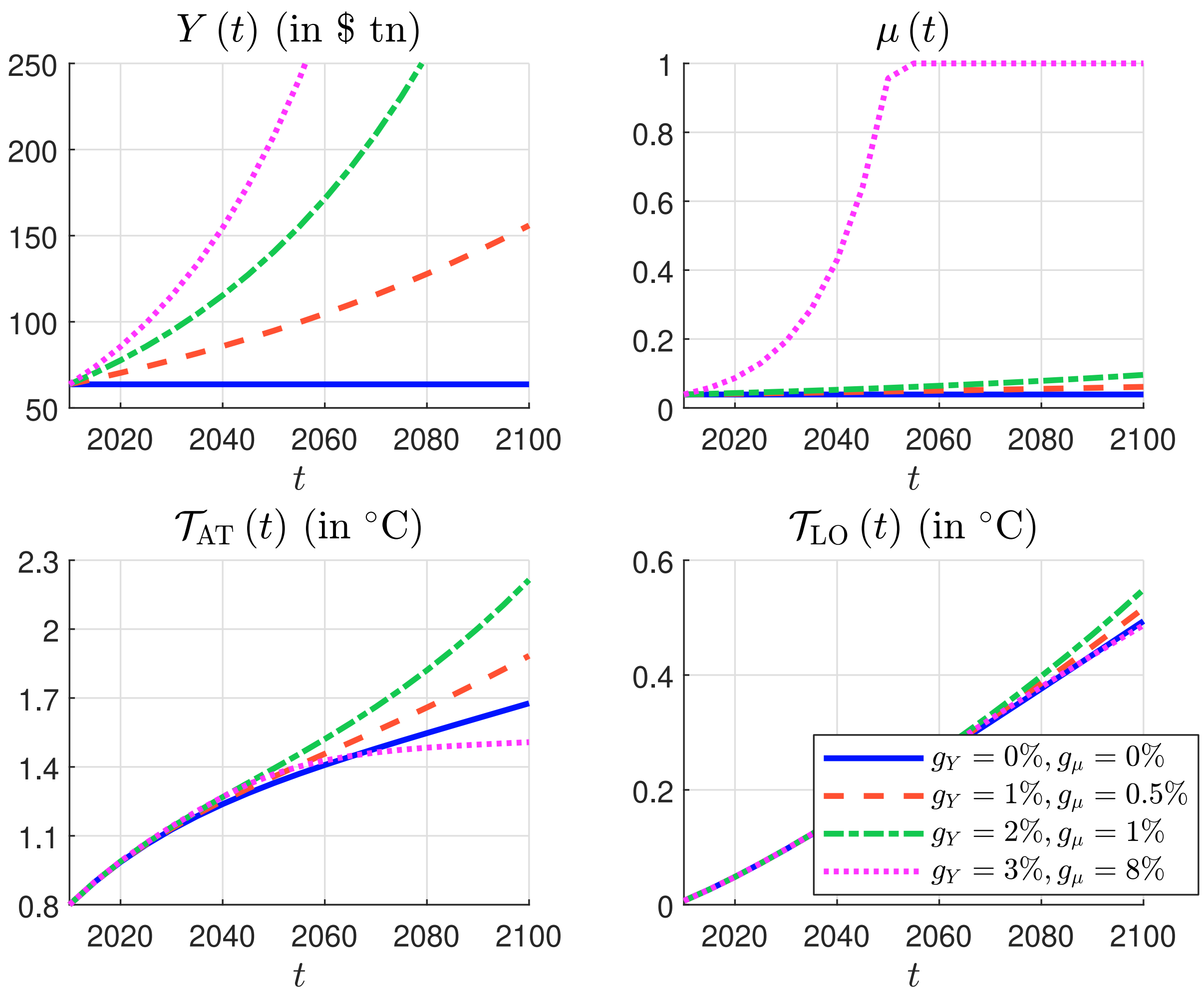
Climate module

Table 2: Output of the DICE climate module ($Y(t) = Y(t_0)$, $\mu(t) = \mu(t_0)$)

t	$\mathcal{CE}(t)$	$\sigma(t)$	$\mathcal{CC}_{\text{AT}}(t)$	$\mathcal{F}_{\text{RAD}}(t)$	$\mathcal{T}_{\text{AT}}(t)$	$\mathcal{T}_{\text{LO}}(t)$
2010	36.91	0.55	830.4	2.14	0.800	0.007
2015	36.25	0.55	825.7	2.14	0.900	0.027
2020	36.06	0.56	821.9	2.14	0.986	0.048
2025	35.97	0.57	818.9	2.14	1.061	0.072
2030	35.98	0.57	816.6	2.15	1.127	0.097
2035	36.05	0.58	814.9	2.16	1.186	0.122
2040	36.18	0.58	813.9	2.18	1.238	0.149
2045	36.36	0.59	813.3	2.20	1.286	0.176
2050	36.58	0.59	813.3	2.23	1.329	0.204
2055	36.82	0.60	813.6	2.26	1.370	0.232
2060	37.09	0.61	814.4	2.29	1.408	0.261
2065	37.39	0.61	815.4	2.32	1.445	0.289
2070	37.70	0.62	816.8	2.35	1.480	0.318
2075	38.02	0.62	818.4	2.39	1.514	0.347
2080	38.36	0.63	820.3	2.43	1.547	0.376
2085	38.71	0.64	822.4	2.46	1.580	0.406
2090	39.06	0.64	824.7	2.50	1.612	0.435
2095	39.43	0.65	827.1	2.55	1.645	0.464
2100	39.80	0.66	829.7	2.59	1.677	0.494

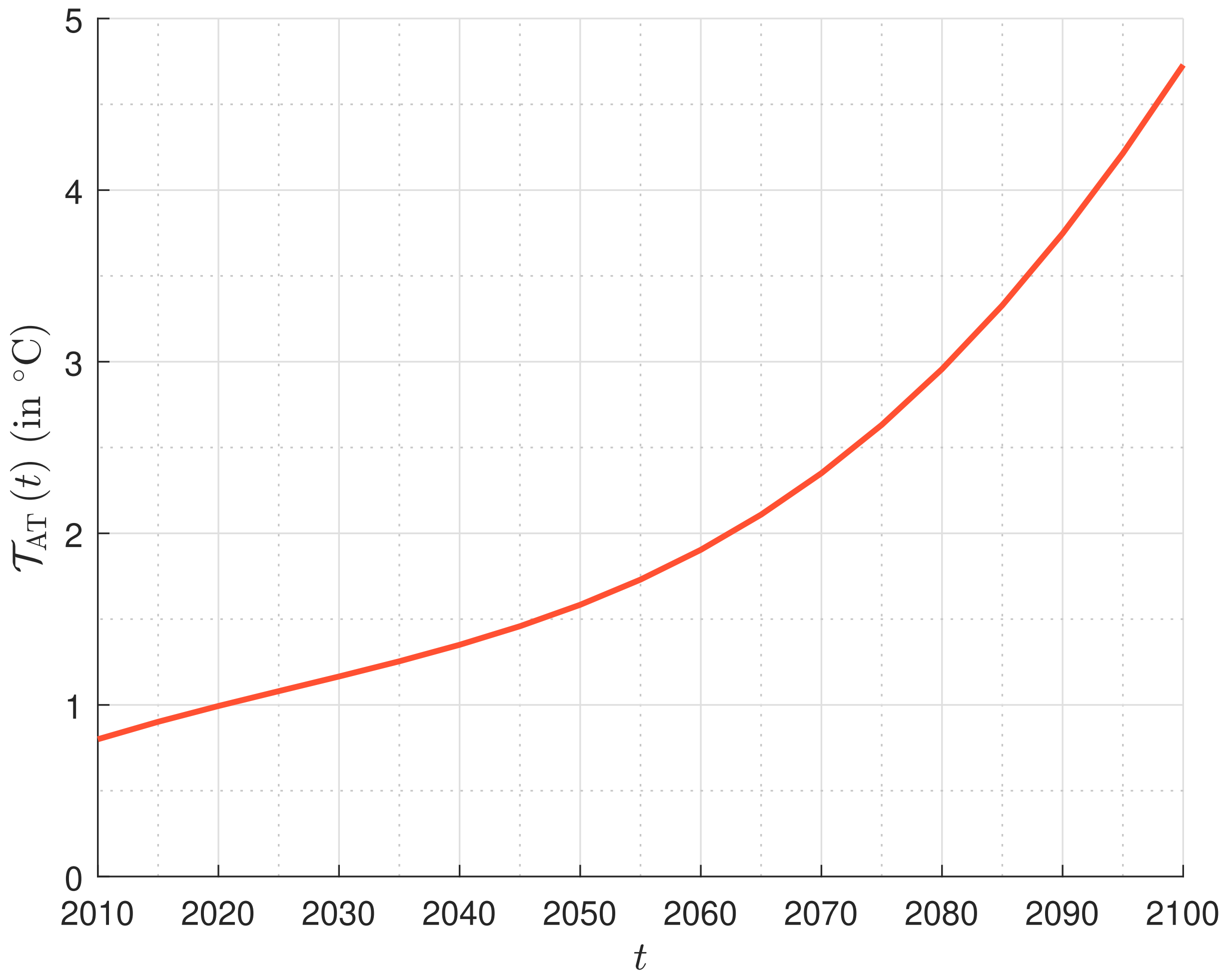
Climate module

Figure 14: Simulation of the DICE climate module



Climate module

Figure 15: The nightmare climate-economic scenario ($g_Y = 0\%$, $\mu(t) = 0$)



The optimal control problem

Optimization problem

- The social welfare function W is equal to:

$$W\left(s\left(t\right),\mu\left(t\right)\right)=\sum_{t=t_0+1}^{T}\frac{L\left(t\right)\mathcal{U}\left(c\left(t\right)\right)}{\left(1+\rho\right)^{t-t_0}}$$

  where ρ is the (generational) discount rate and $c\left(t\right)=C\left(t\right)/L\left(t\right)$ is the consumption per capita
- $\mathcal{U}\left(c\right)=\left(c^{1-\alpha}-1\right)/\left(1-\alpha\right)$ is the CRRA utility function
- The optimal control problem is then given by:

$$\begin{aligned}\left(s^{\star}\left(t\right),\mu^{\star}\left(t\right)\right) & = & \arg\max W\left(s\left(t\right),\mu\left(t\right)\right) \\ & & \text{s.t.}\quad\left\{\begin{array}{l}\text{DICE Equations}\\ \mu\left(t\right)\in\left[0,1\right]\\ s\left(t\right)\in\left[0,1\right]\end{array}\right.\end{aligned}$$

The optimal control problem

The important variables are:

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

Social cost of carbon (SCC)

"The most important single economic concept in the economics of climate change is the social cost of carbon (SCC). This term designates the economic cost caused by an additional tonne of carbon dioxide emissions or its equivalent. In a more precise definition, it is the change in the discounted value of economic welfare from an additional unit of COtwo-equivalent emissions. The SCC has become a central tool used in climate change policy, particularly in the determination of regulatory policies that involve greenhouse gas emissions." (Nordhaus, 2017).

Social cost of carbon (SCC)

Mathematical definition

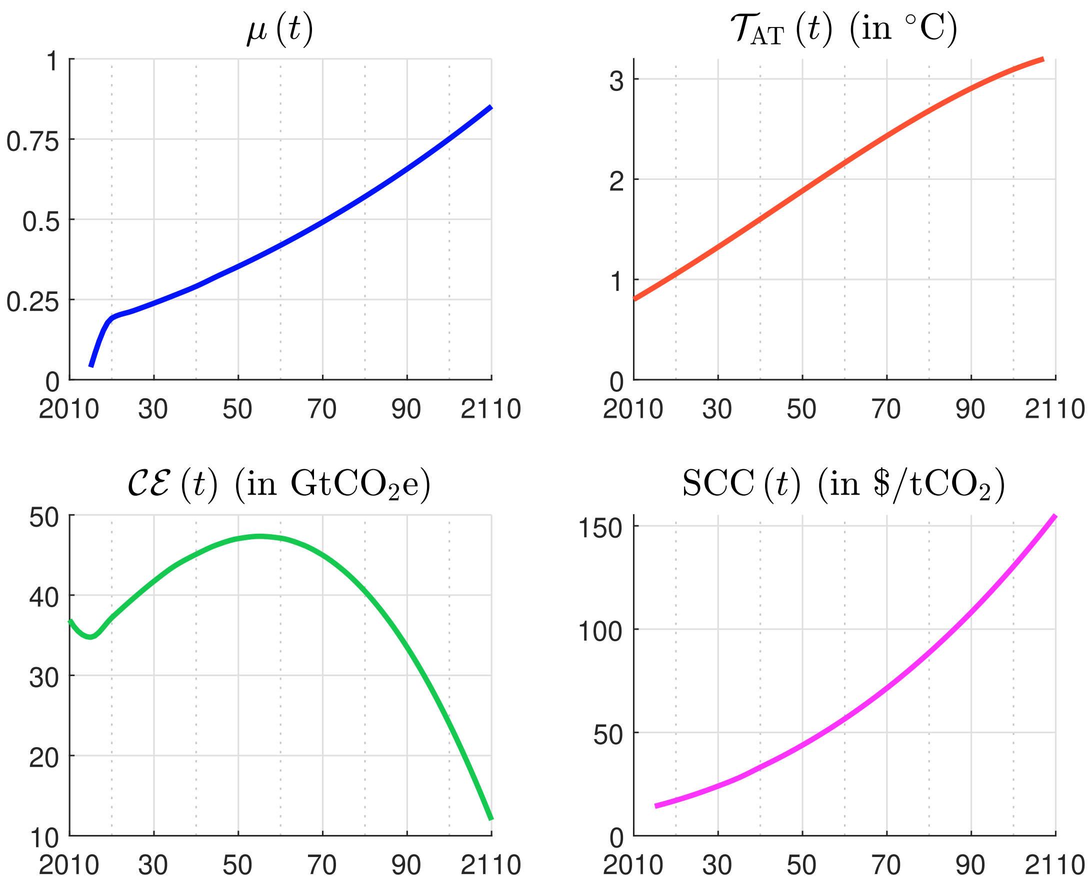
- The social cost of carbon is then defined as:

$$\mathrm{SCC}(t) = \frac{\dfrac{\partial\, W(t)}{\partial\, \mathcal{CE}(t)}}{\dfrac{\partial\, W(t)}{\partial\, C(t)}} = \frac{\partial\, C(t)}{\partial\, \mathcal{CE}(t)}$$

- It is expressed in $\$/\mathrm{tCO}_2$

Social cost of carbon (SCC)

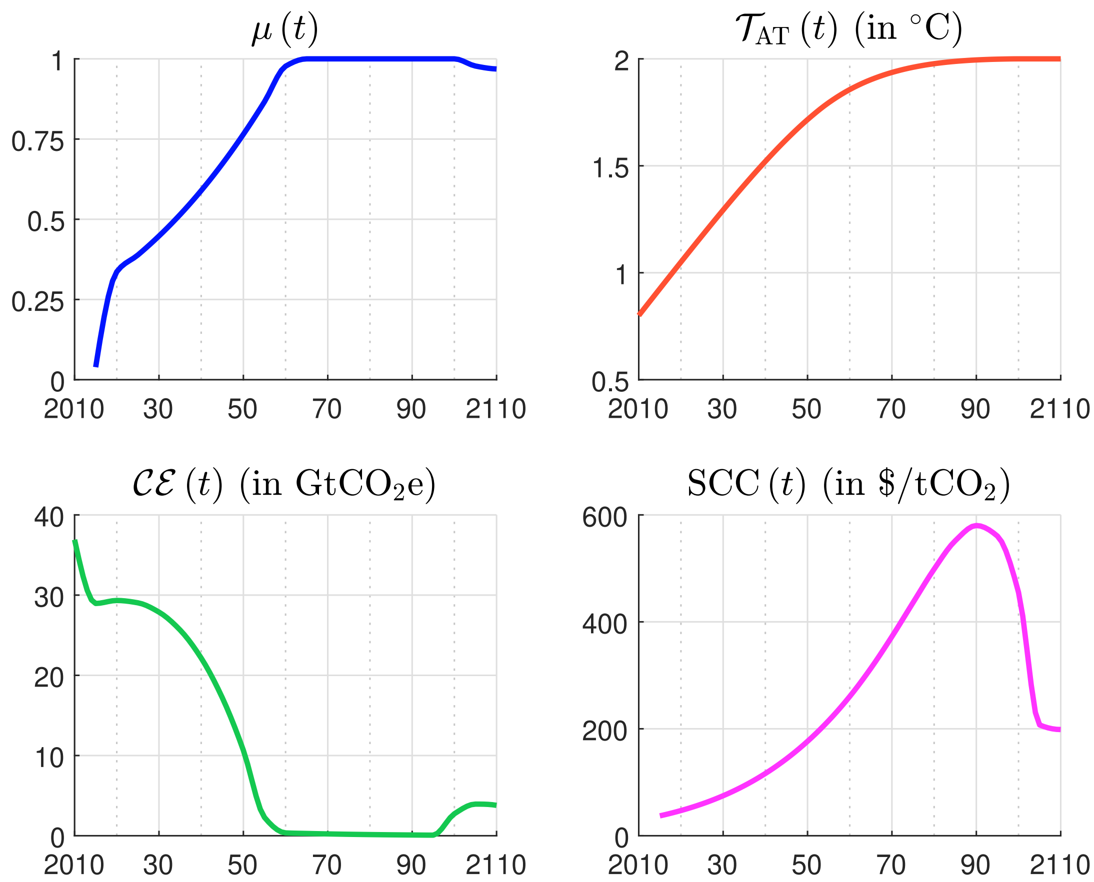
Figure 16: Optimal welfare scenario (DICE 2013R)



Source: Le Guenedal (2019).

Social cost of carbon (SCC)

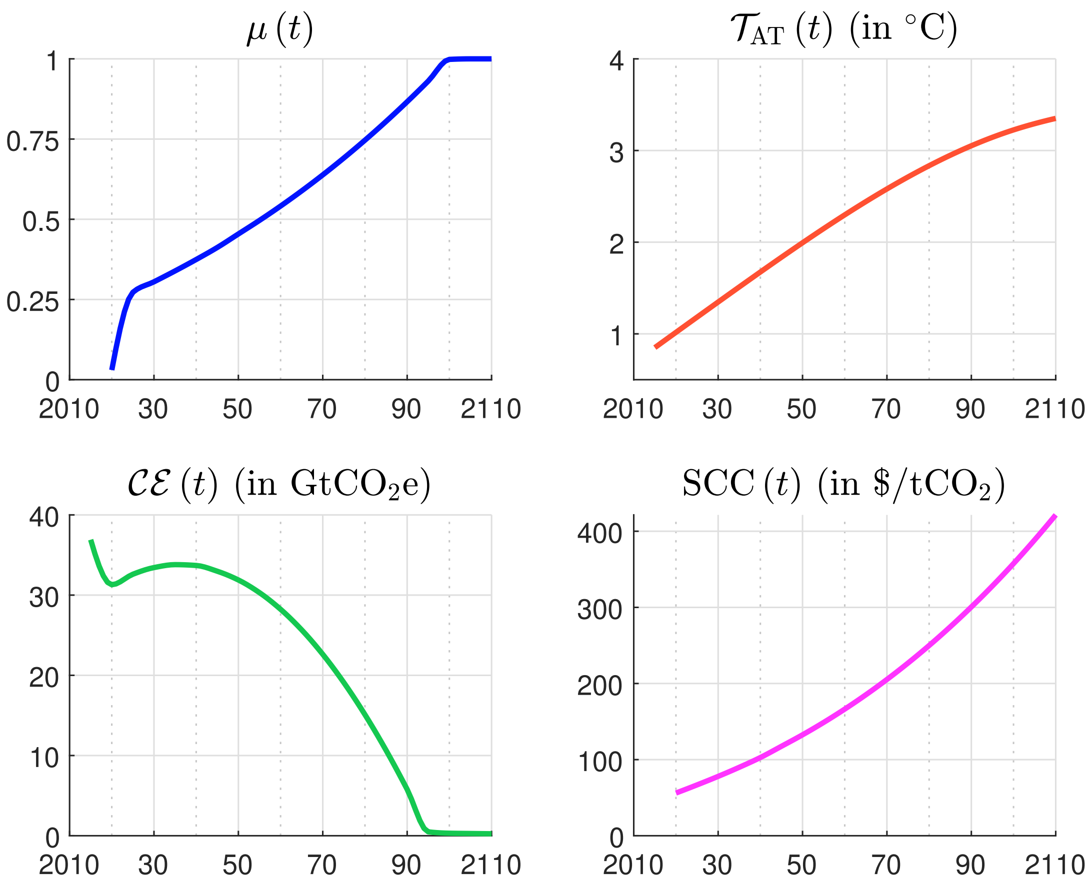
Figure 17: 2°C scenario (DICE 2013R)



Source: Le Guenedal (2019).

Social cost of carbon (SCC)

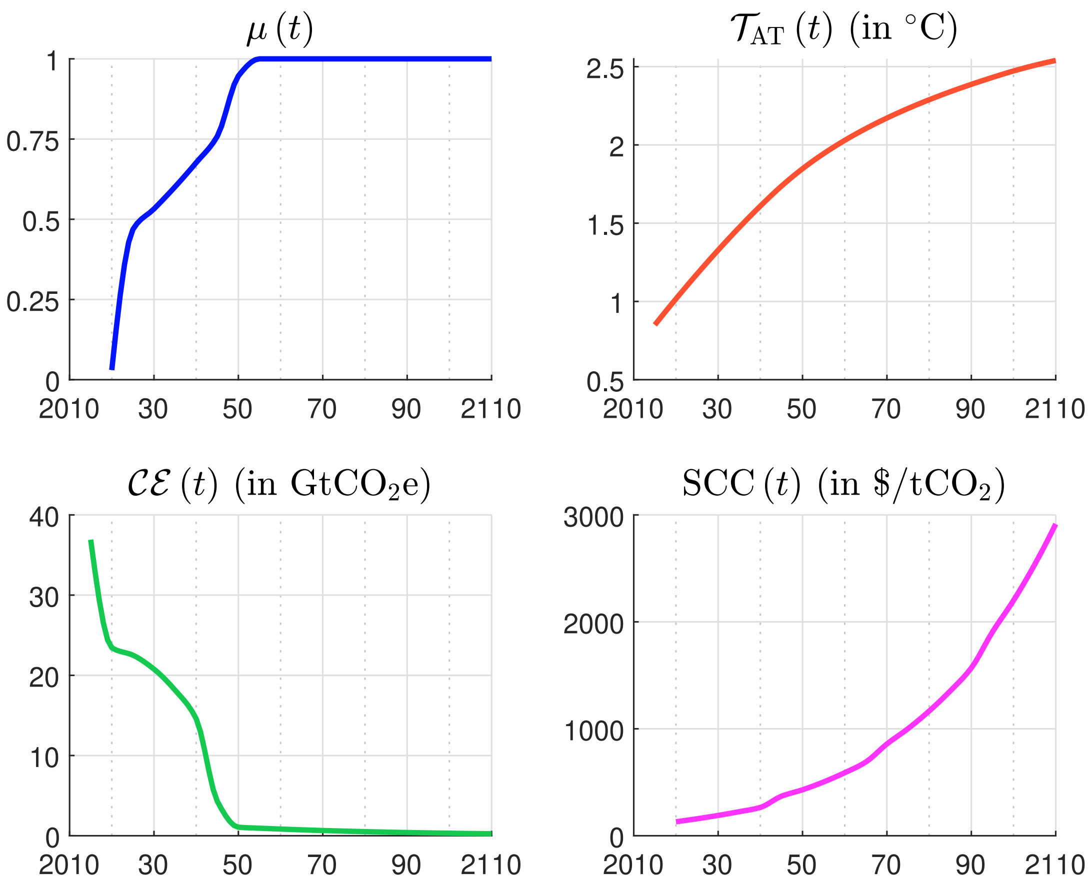
Figure 18: Optimal welfare scenario (DICE 2016R)



Source: Le Guenedal (2019).

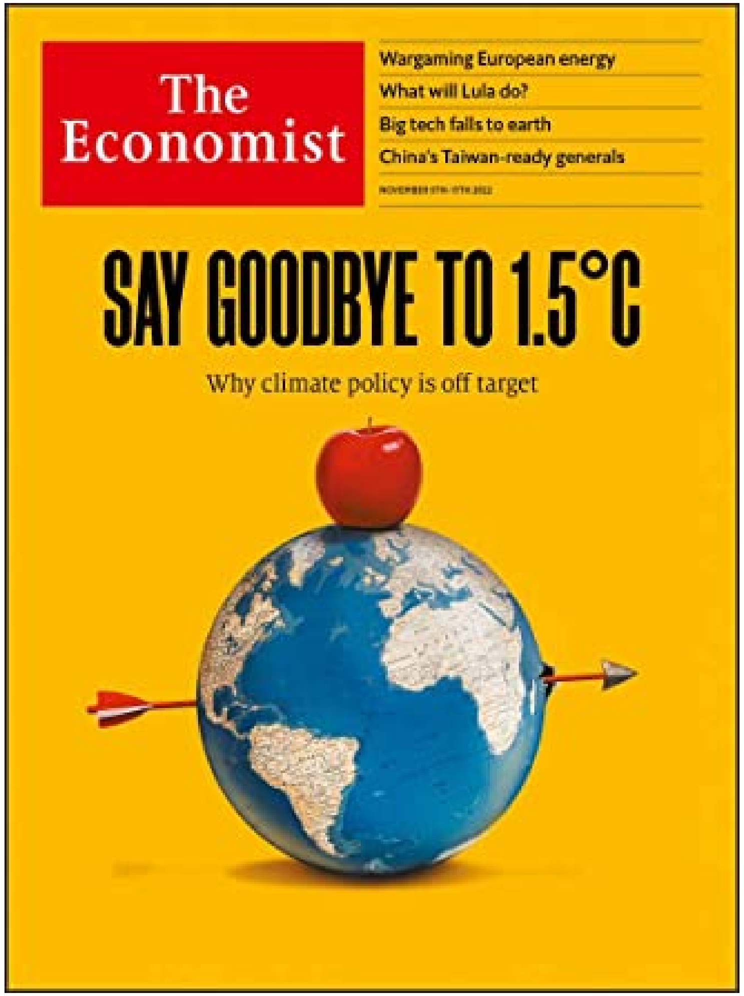
Social cost of carbon (SCC)

Figure 19: 2°C scenario (DICE 2016R)



Source: Le Guenedal (2019).

The tragedy of the horizon



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 $\approx$ 2.6°C)
- For many models, we now have:

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

Social cost of carbon (SCC)

Table 3: Global SCC under different scenario assumptions (in $\$/tCO_2$)

Scenario	2015	2020	2025	2030	2050	CAGR
Baseline	31.2	37.3	44.0	51.6	102.5	3.46%
Optimal	30.7	36.7	43.5	51.2	103.6	3.54%
2.5°C-max	184.4	229.1	284.1	351.0	1 006.2	4.97%
2.5°C-mean	106.7	133.1	165.1	203.7	543.3	4.76%

Source: Nordhaus (2017).

Social cost of carbon (SCC)

The Stern-Nordhaus controversy

- In 2007, Nicholas Stern published a report called **The Economics of Climate Change: The Stern Review**
- The Stern Review called for sharp and immediate action to stabilize greenhouse gases because:

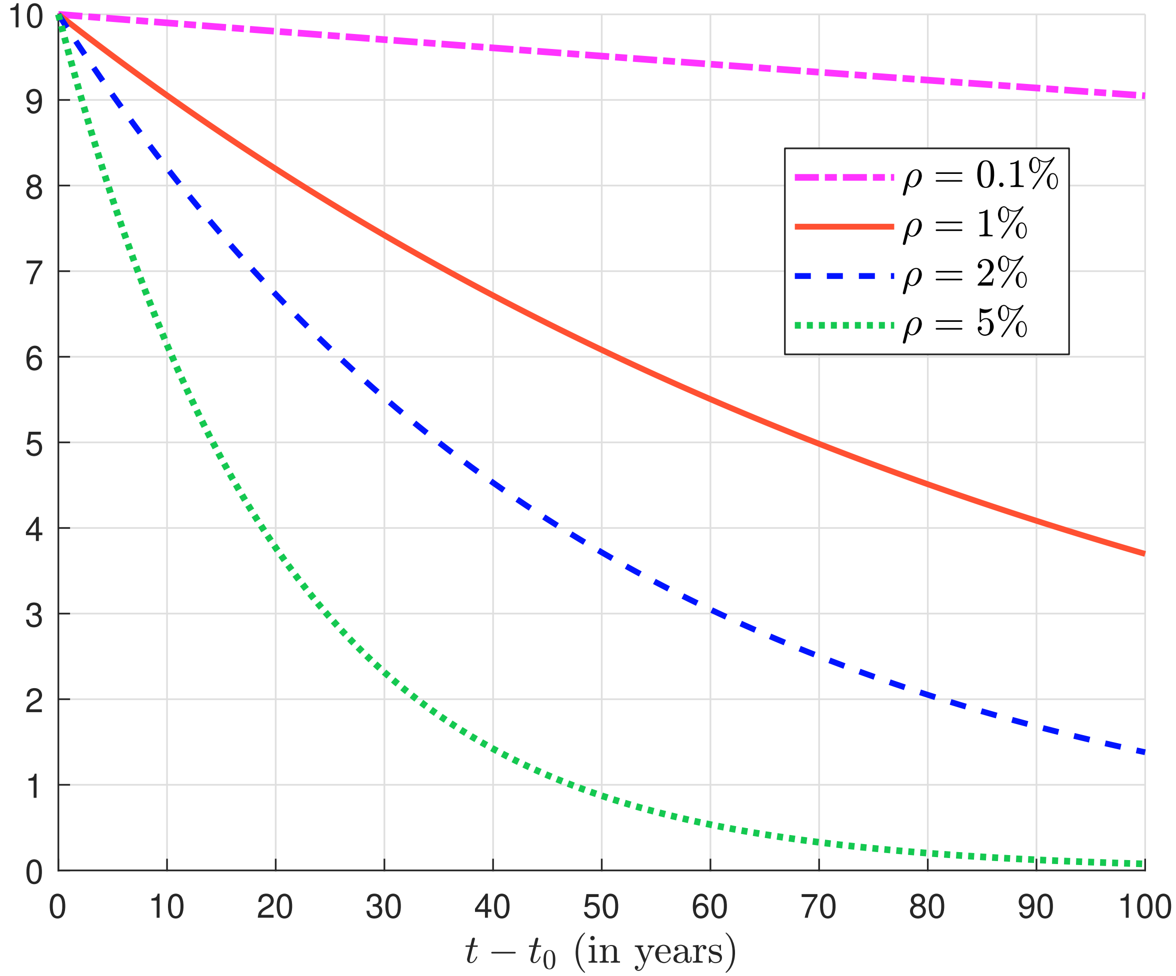
  "**the benefits of strong, early action on climate change outweighs the costs**"

- The Stern Review proposes to use $\rho = \mathbf{0.10\%}$

Social cost of carbon (SCC)

The Stern-Nordhaus controversy

Figure 20: Discounted value of $10



Social cost of carbon (SCC)

The Stern-Nordhaus controversy

- The time (or generational) discount rate ρ is also called the pure rate of time preference
- It is related to the Ramsey rule:

$$r = \rho + \alpha g$$

where:

  - r is the real interest rate
  - $g = \partial\, c(t) / c(t)$ is the growth rate of per capita consumption
  - α is the consumption elasticity of the utility function

Social cost of carbon (SCC)

The Stern-Nordhaus controversy

We report the computations done by Dasgupta (2008):

Model	ρ	α	g_c	r
Cline (1992)	0.0%	1.5	1.3%	2.05%
Nordhaus (2007)	3.0%	1.0	1.3%	4.30%
Stern (2007)	0.1%	1.0	1.3%	1.40%

Social cost of carbon (SCC)

The Stern-Nordhaus controversy

Table 4: Global SCC under different discount rate assumptions

Discount rate	2015	2020	2025	2030	2050	CAGR
Stern	197.4	266.5	324.6	376.2	629.2	3.37%
Nordhaus	30.7	36.7	43.5	51.2	103.6	3.54%
2.5%	128.5	140.0	152.0	164.6	235.7	1.75%
3%	79.1	87.3	95.9	104.9	156.6	1.97%
4%	36.3	40.9	45.8	51.1	81.7	2.34%
5%	19.7	22.6	25.7	29.1	49.2	2.65%

Source: Nordhaus (2017).

Some models

- 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

Some models

Table 5: Main integrated assessment models

Model	Reference	Name
Stylized simple models		
DICE	Nordhaus and Sztorc (2013)	Dynamic Integrated Climate-Economy
FUND	Anthoff and Tol (2014)	Climate Framework for Uncertainty, Negotiation and Distribution
PAGE	Hope (2011)	Policy Analysis of the Greenhouse Effect
Complex models		
AIM/CGE	Fujimori *et al.* (2017)	Asia-Pacific Integrated Model/Computable General Equilibrium
GCAM	Calvin *et al.* (2019)	Global Change Assessment Model
GLOBIOM	Havlik *et al.* (2018)	Global Biosphere Management Model
IMACLIM-R	Sassi *et al.* (2010)	Integrated Model to Assess Climate Change
IMAGE	Stehfest *et al.* (2014)	Integrated Model to Assess the Greenhouse Effect
MAGICC	Meinshausen *et al.* (2011)	Model for the Assessment of Greenhouse Gas Induced Climate Change
MAgPIE	Dietrich *et al.* (2019)	Model of Agricultural Production and its Impact on the Environment
MESSAGEix	Huppmann *et al.* (2019)	Model for Energy Supply Strategy Alternatives and their General Environmental Impact
REMIND	Aboumahboub *et al.* (2020)	REgional Model of INvestments and Development
WITCH	Bosetti *et al.* (2006)	World Induced Technical Change Hybrid

Source: Grubb *et al.* (2021) & Author's research.

Stylized IAMs

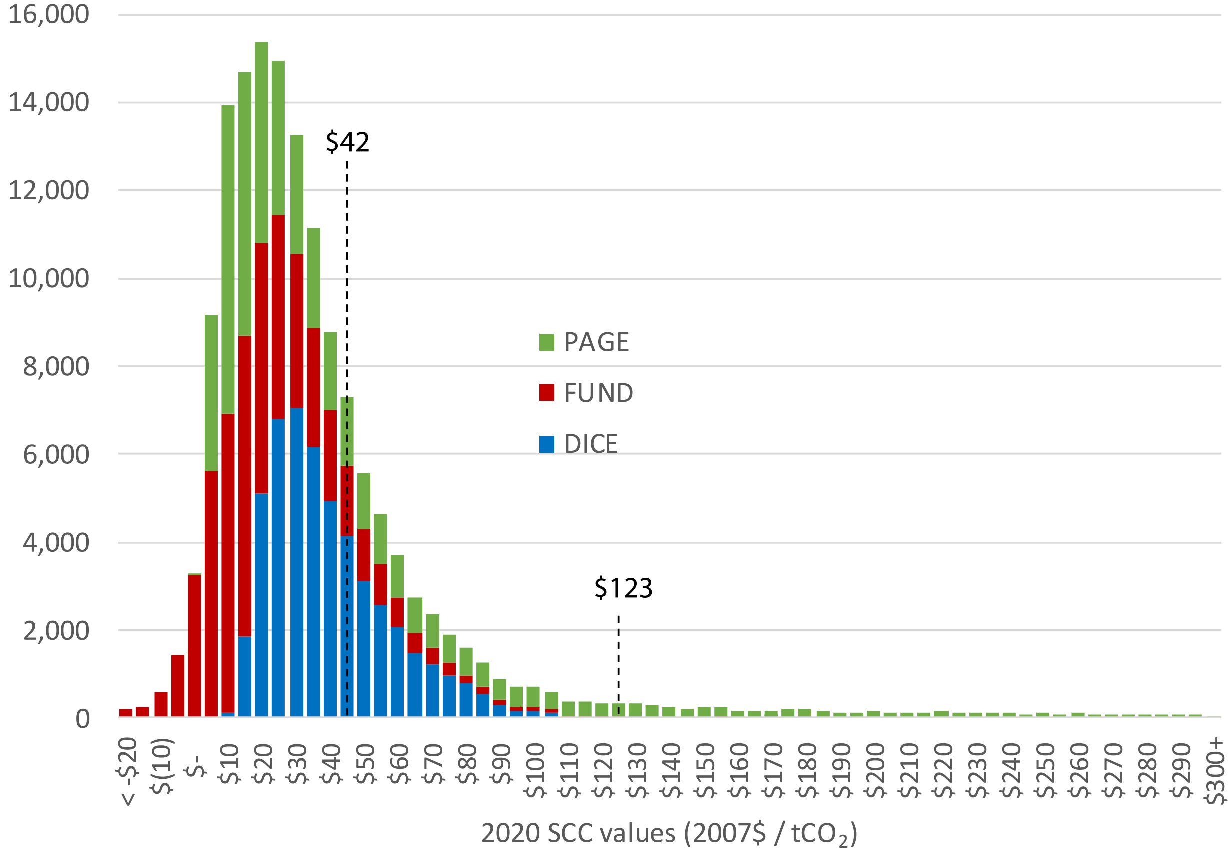
The Leaders

- DICE
- FUND
- PAGE

$\Rightarrow$ SCC: PAGE $\succ$ DICE $\succ$ FUND

Stylized IAMs

Figure 21: Histogram of the 150 000 US Government SCC estimates for 2020 with a 3% discount rate

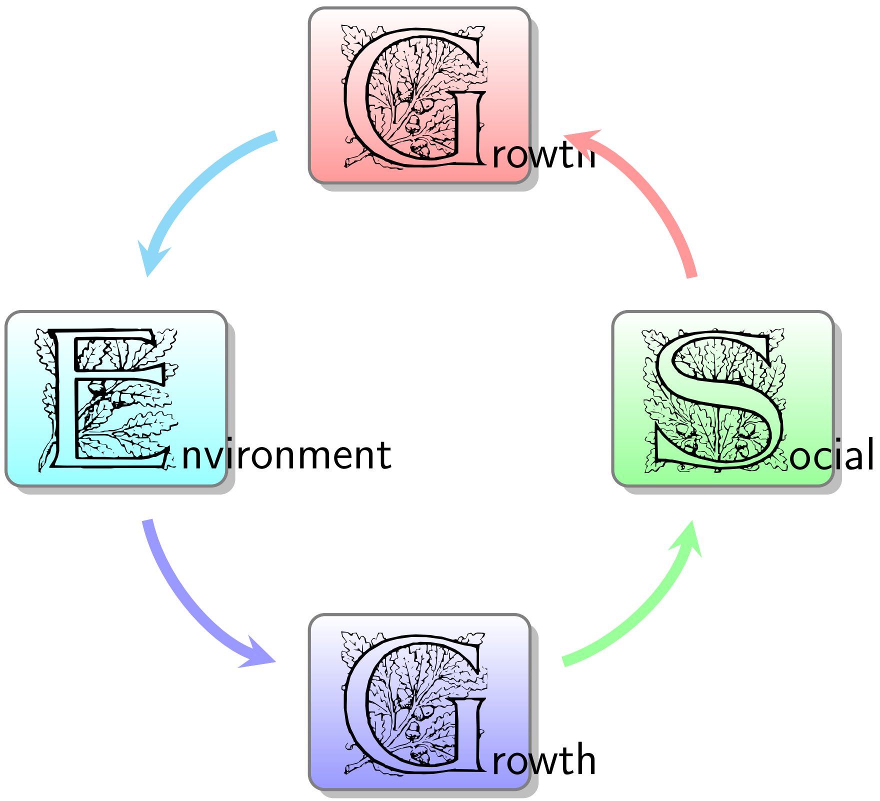


Source: Rose *et al.* (2017).

Stylized IAMs

The liability/fairness question

Liability



Aristotle (384 BC – 322 BC)
ΗΘΙΚΩΝ ΝΙΚΟΜΑΧΕΙΩΝ

Karl Marx and Friedrich Engels (1848)
The Communist Manifesto

Stylized IAMs
The liability/fairness question

Fairness

Du Contrat Social

Stylized IAMs

Climate risk and inequalities

Three types of inequalities

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

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

Stylized IAMs

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

Stylized IAMs

Social inequalities

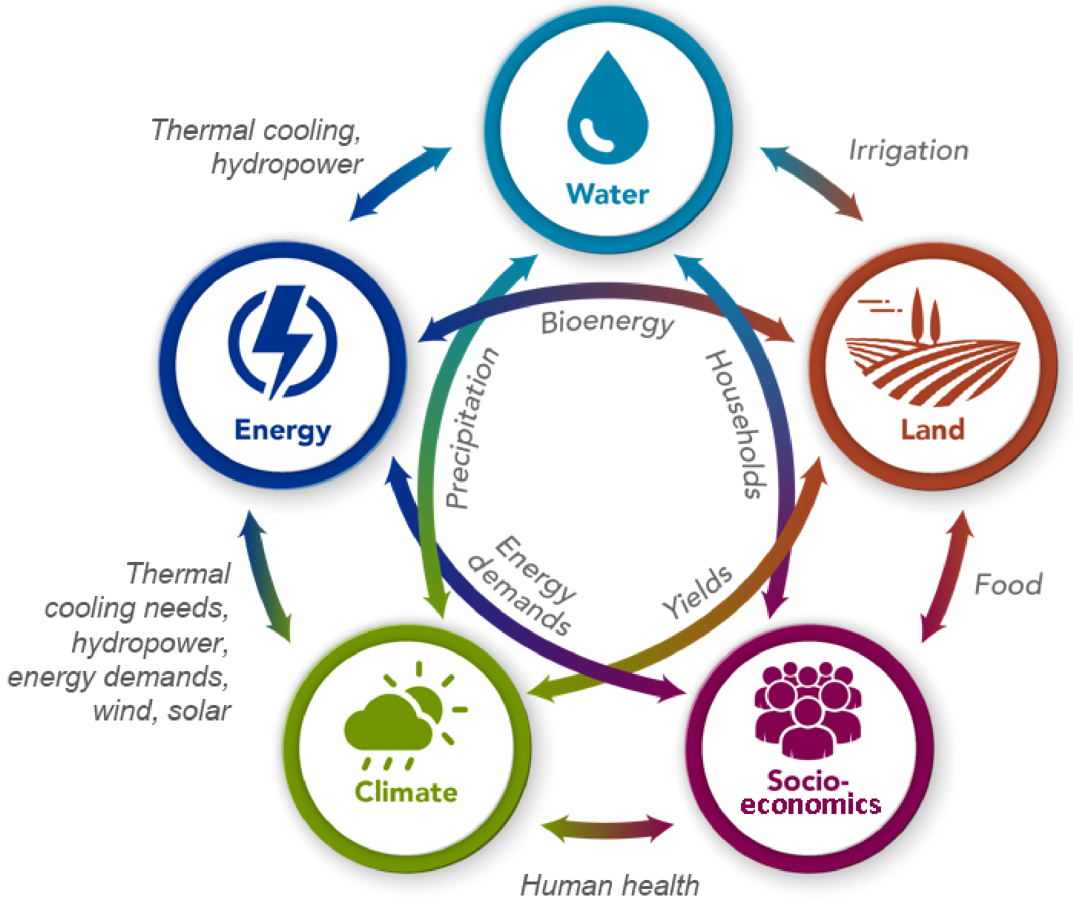
The **N**ested **I**nequalities **C**limate-**E**conomy (NICE) model integrates distributional differences of income (Dennig *et al.*, 2015)

> *"[...] 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

Complex IAMs

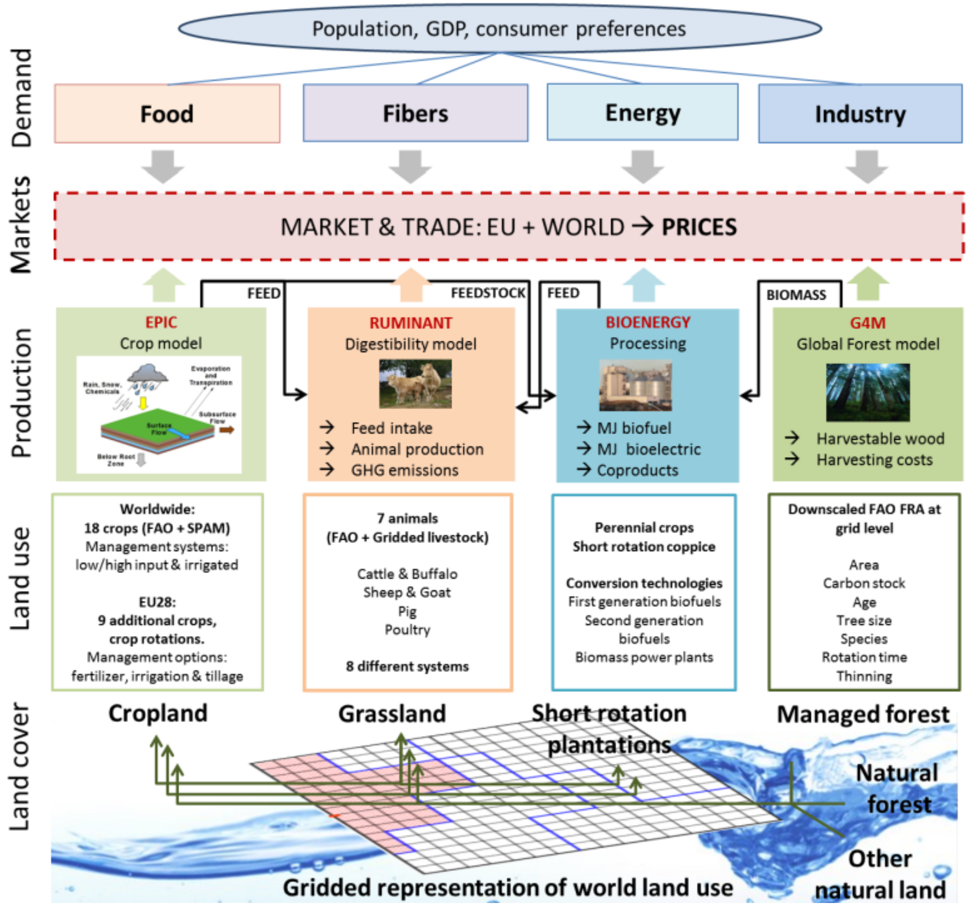
Figure 22: Linkages between the major systems in GCAM



Source: Calvin *et al.* (2019).

Complex IAMs

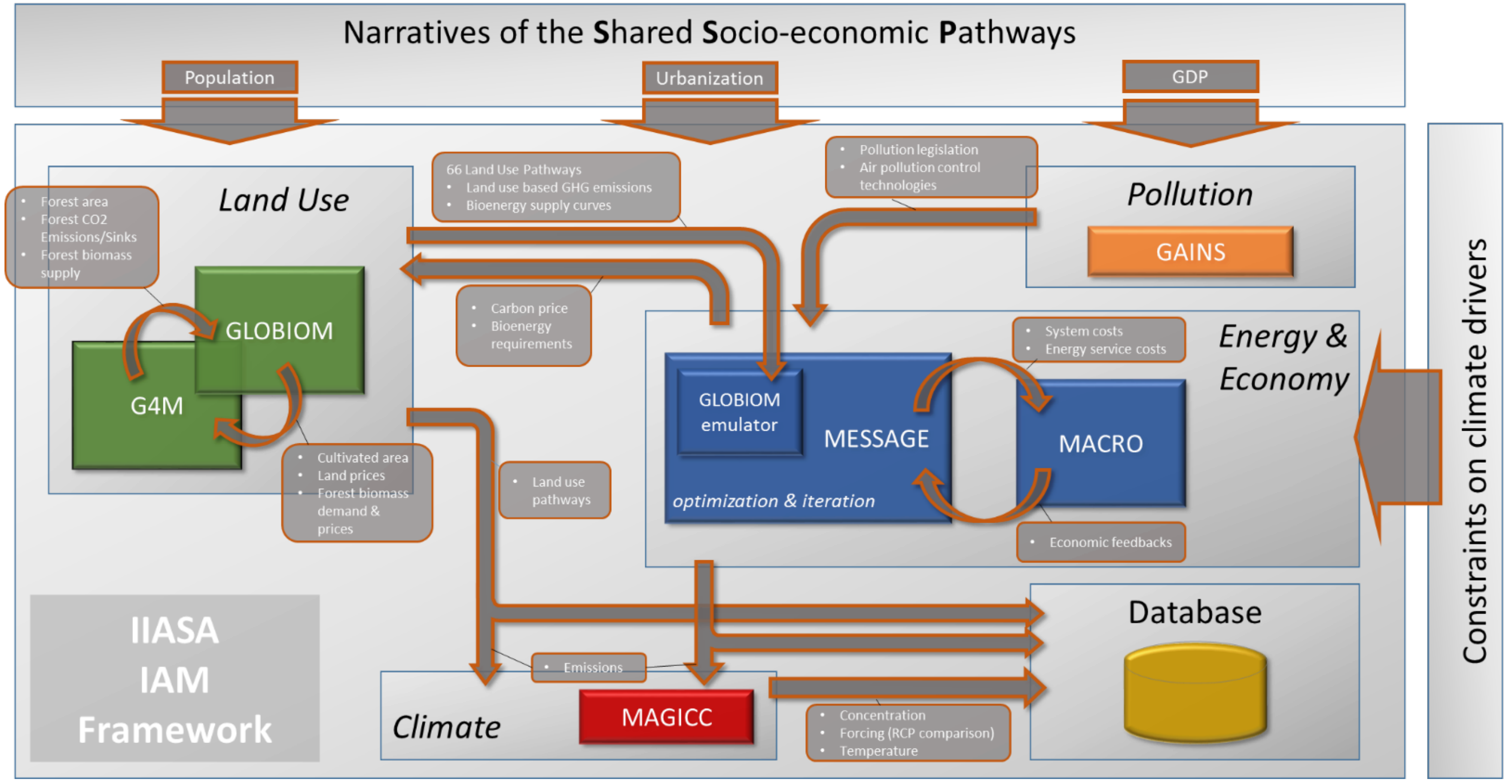
Figure 23: The main land use sectors of GLOBIOM



Source: https://iiasa.github.io/GLOBIOM.

Complex IAMs

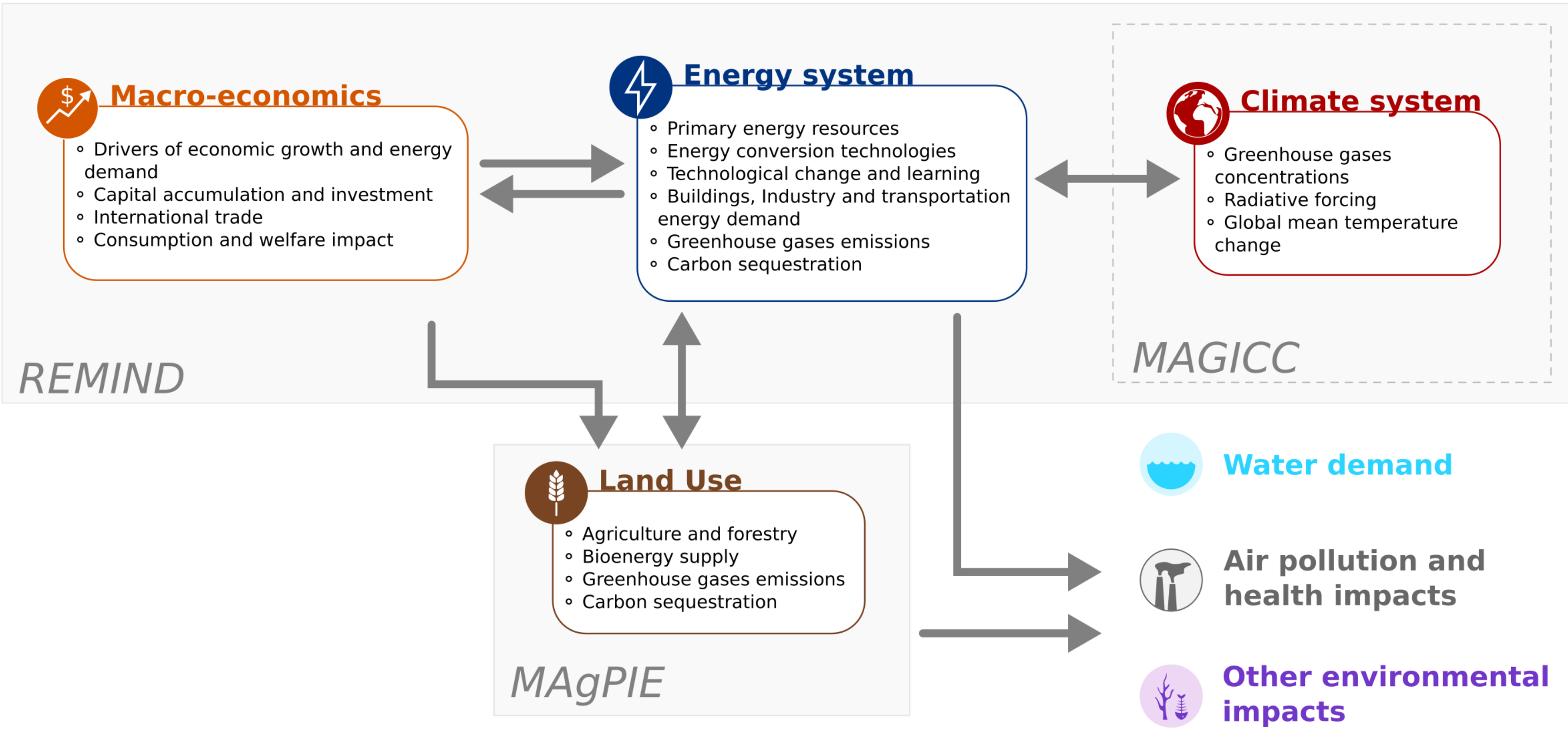
Figure 24: Overview of the IIASA IAM framework



Source: https://docs.messageix.org/projects/global/en/latest/overview/index.html.

Complex IAMs

Figure 25: The Remind-MAgPIE framework



Source: `www.pik-potsdam.de/en/institute/departments/transformation-pathways/models/remind`.

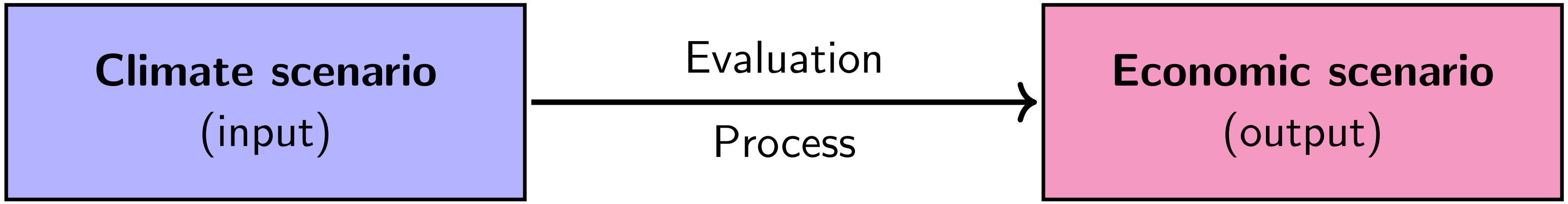
Criticisms of integrated assessment models

"IAM-based analyses of climate policy create a perception of knowledge and precision that is illusory and can fool policymakers into thinking that the forecasts the models generate have some kind of scientific legitimacy" (Pindyck, 2017)

- Certain inputs, such as the discount rate, are arbitrary
- There is a lot of uncertainty about climate sensitivity and the temperature trajectory
- Modeling damage functions is arbitrary
- IAMs are unable to consider tail risk

Scenarios

Figure 26: Scenario evaluation



Climate scenarios

- The representative concentration pathways (RCPs) — IPCC AR5
- The IEA scenarios
- The 1.5°C scenarios — SR15
- The scenarios for the future published — IPCC AR6

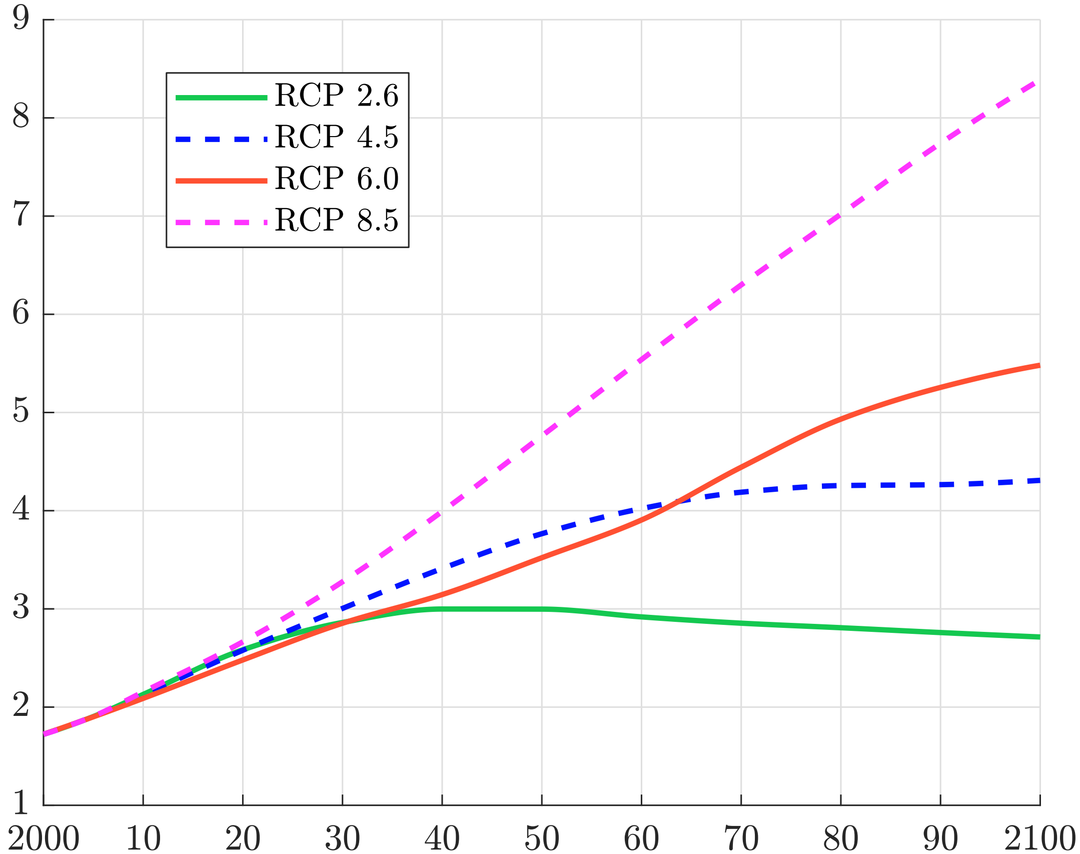
Climate scenarios

The RCP scenarios

1. RCP 2.6: GHG emissions start declining by 2020 and go to zero by 2100 (IMAGE)
2. RCP 4.5: GHG emissions peak around 2040, and then decline (MiniCAM)
3. RCP 6.0: GHG emissions peak around 2080, and then decline (AIM)
4. RCP 8.5: GHG emissions continue to rise throughout the 21st century (MESSAGE)

Climate scenarios
The RCP scenarios

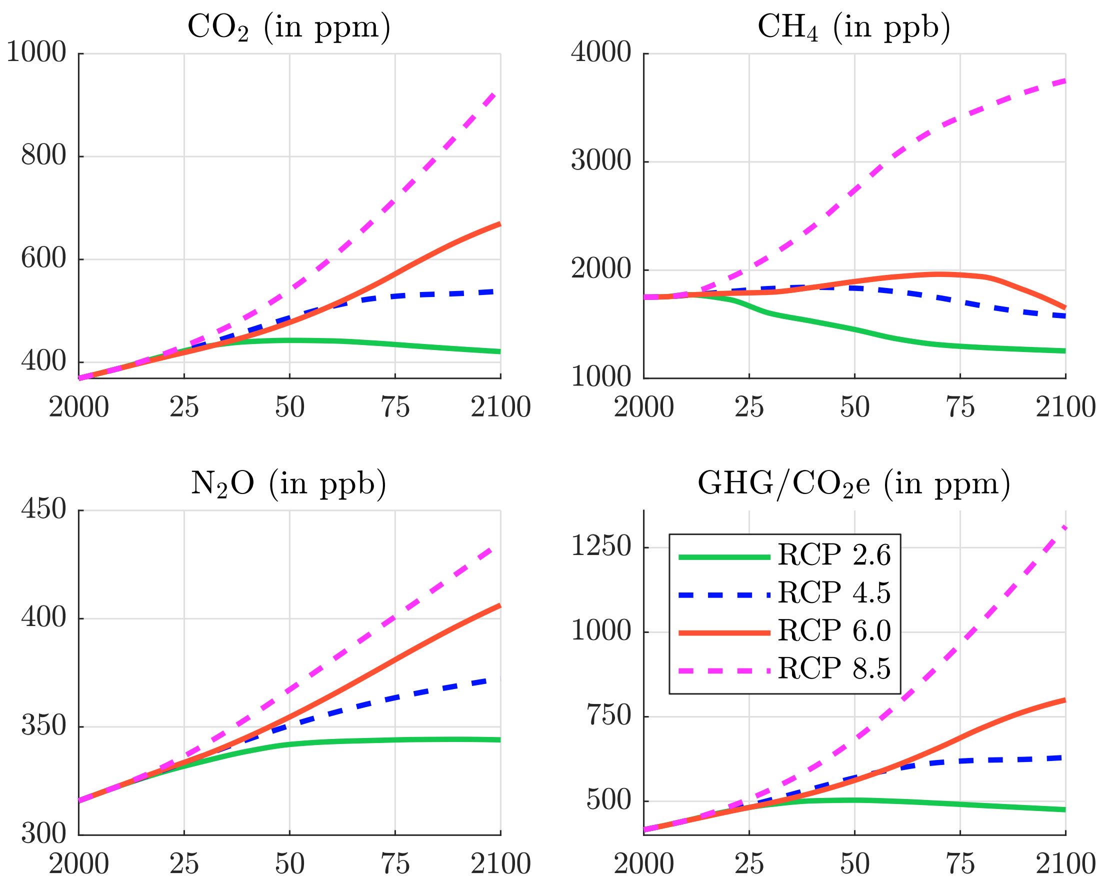
Figure 27: Total radiative forcing (in $\mathrm{W/m^2}$)



Source: `https://tntcat.iiasa.ac.at/RcpDb`.

Climate scenarios
The RCP scenarios

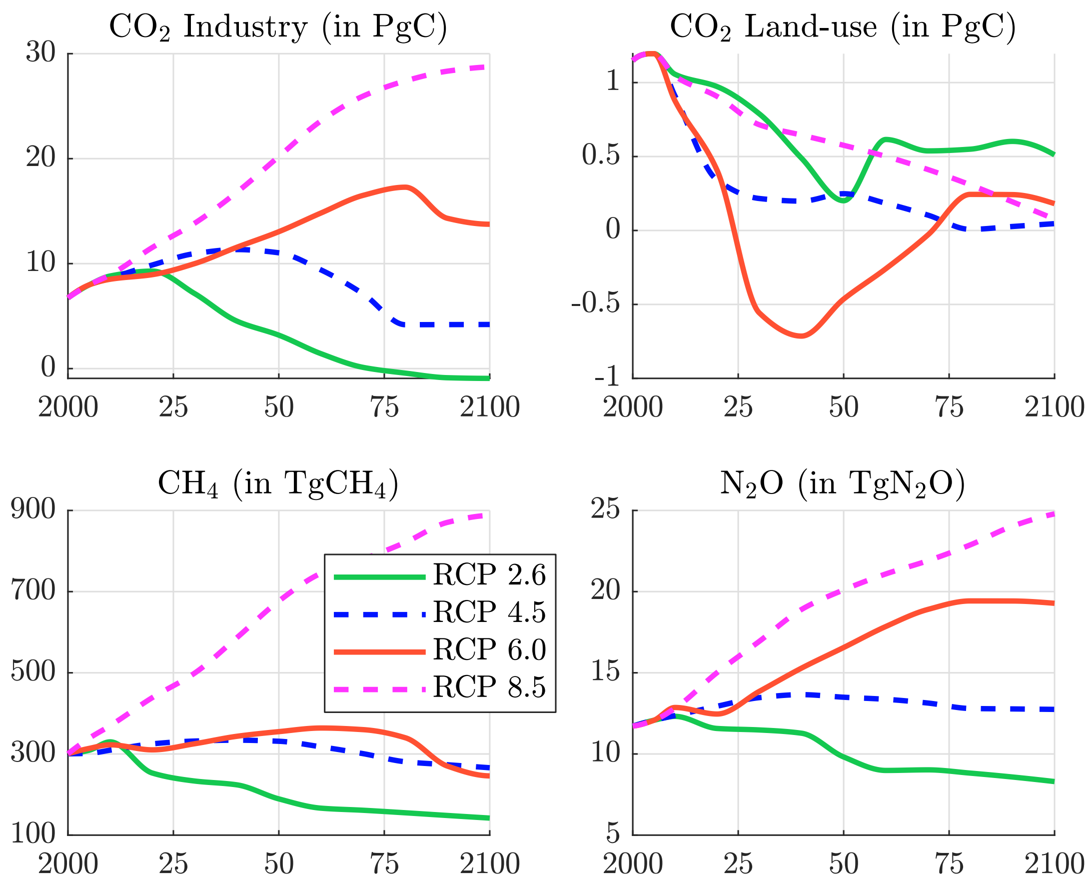
Figure 28: Greenhouse gas concentration trajectory



Source: `https://tntcat.iiasa.ac.at/RcpDb`.

Climate scenarios
The RCP scenarios

Figure 29: Greenhouse gas emissions trajectory

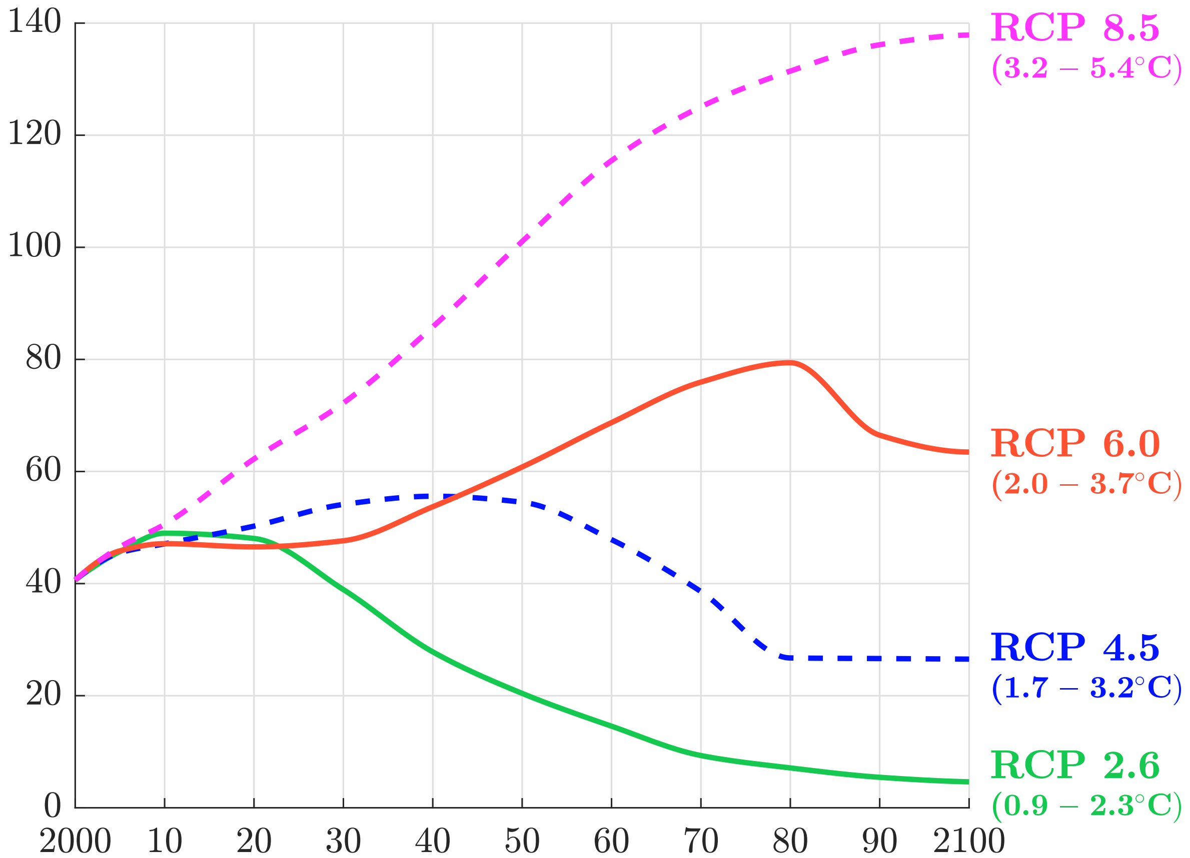


Source: `https://tntcat.iiasa.ac.at/RcpDb`.

Climate scenarios

The RCP scenarios

Figure 30: Total GHG emissions trajectory (in $GtCO_2e$)

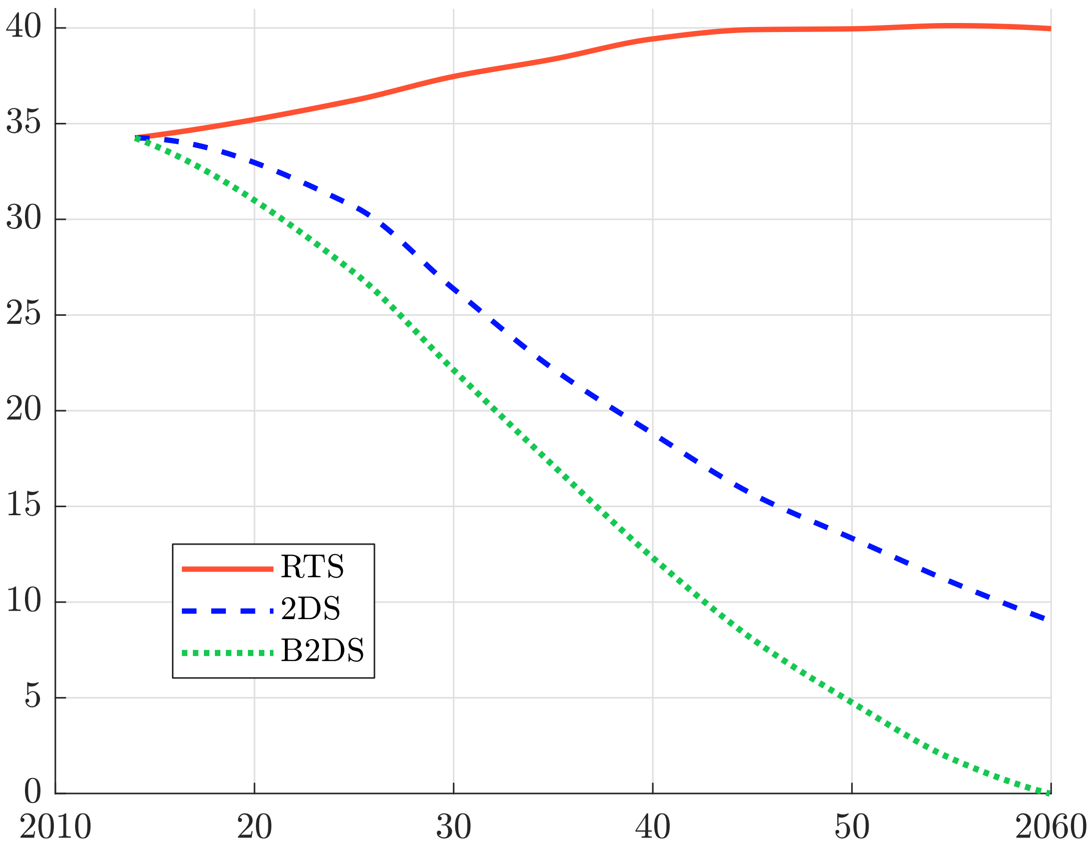


Source: `https://tntcat.iiasa.ac.at/RcpDb`.

Climate scenarios

The IEA scenarios

Figure 31: Direct CO_2 emissions (in Gt)

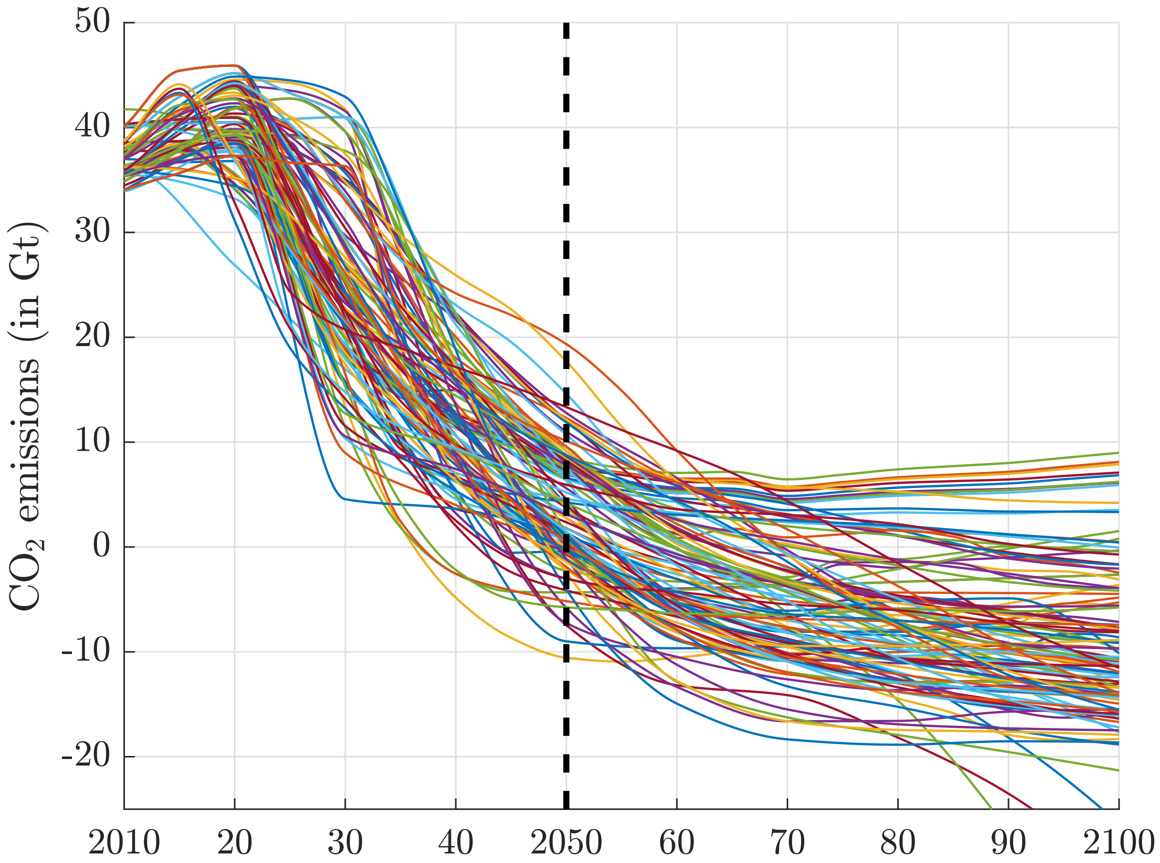


Source: IEA (2017).

Climate scenarios

The 1.5°C scenarios

Figure 32: IPCC 1.5°C scenarios of CO_2 emissions

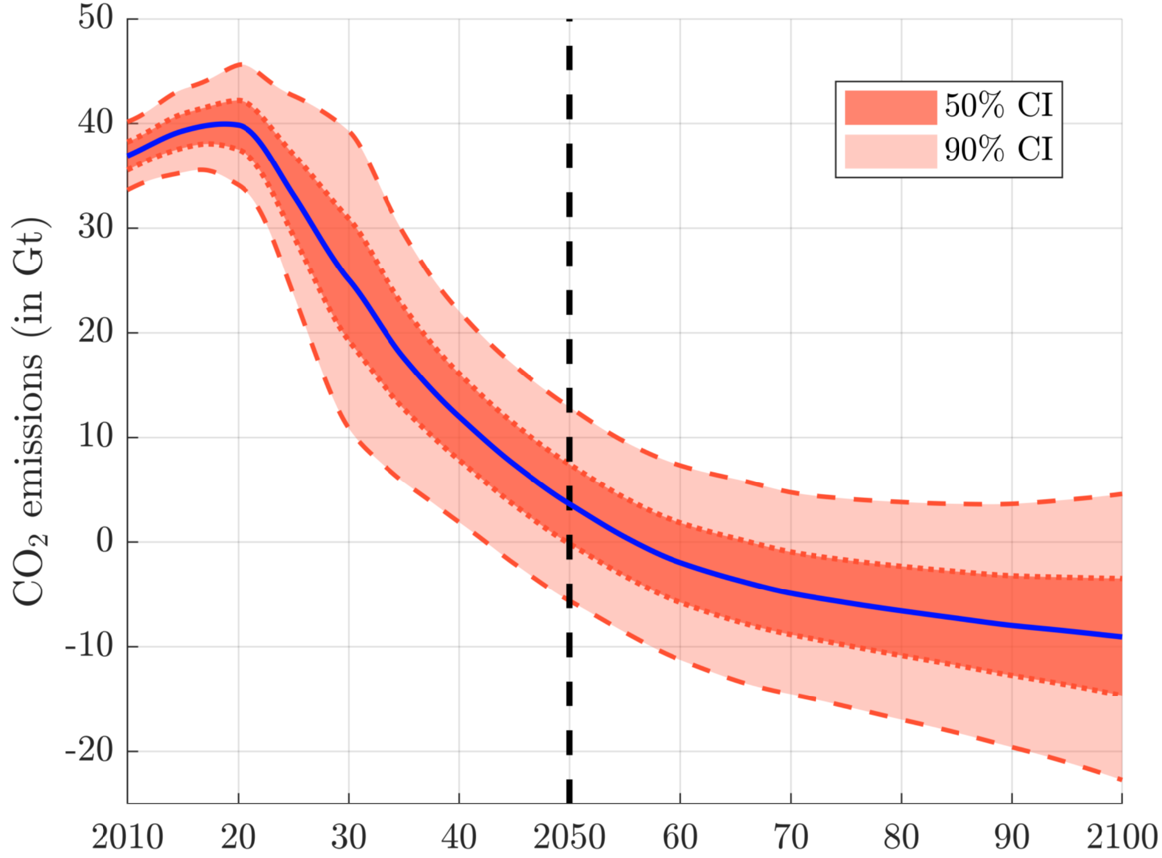


Source: `https://data.ene.iiasa.ac.at/iamc-1.5c-explorer`.

Climate scenarios

The 1.5°C scenarios

Figure 33: Confidence interval of the average IPCC 1.5°C scenario

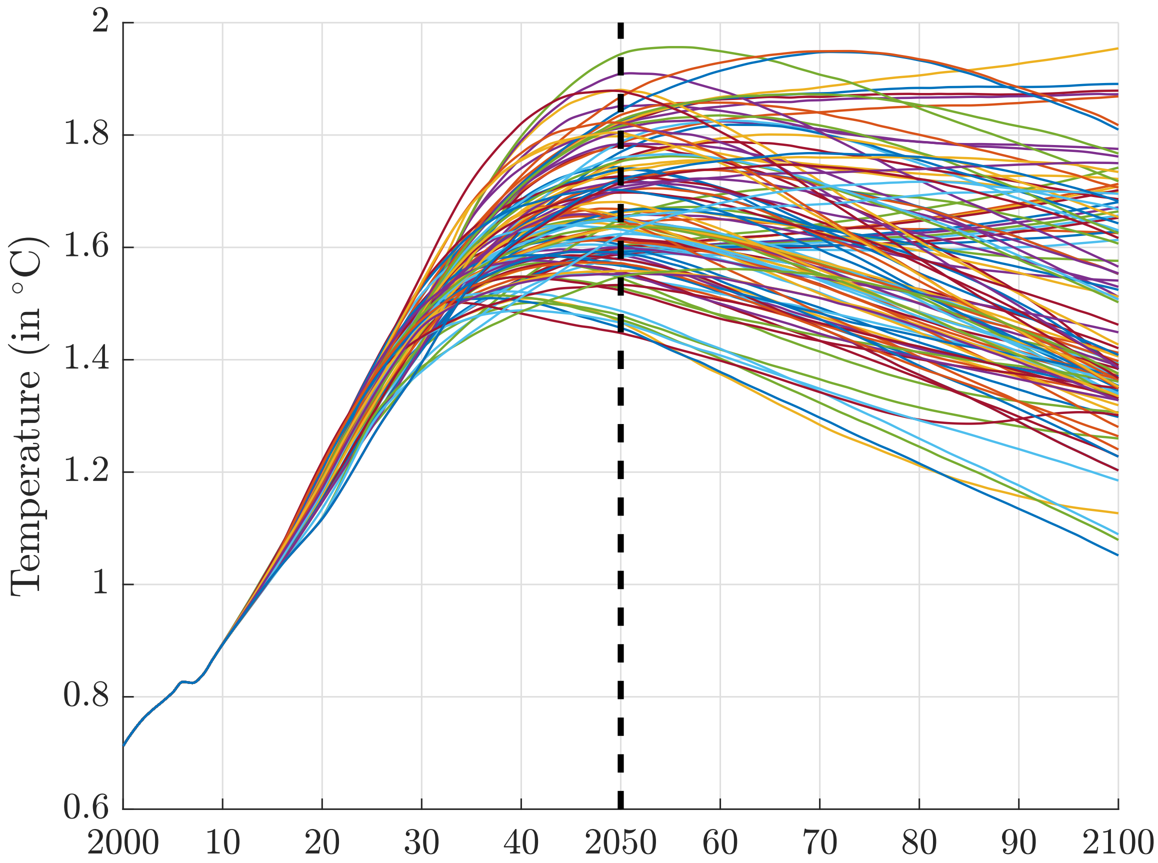


Source: `https://data.ene.iiasa.ac.at/iamc-1.5c-explorer`.

Climate scenarios

The 1.5°C scenarios

Figure 34: IPCC 1.5°C scenarios of the global mean temperature

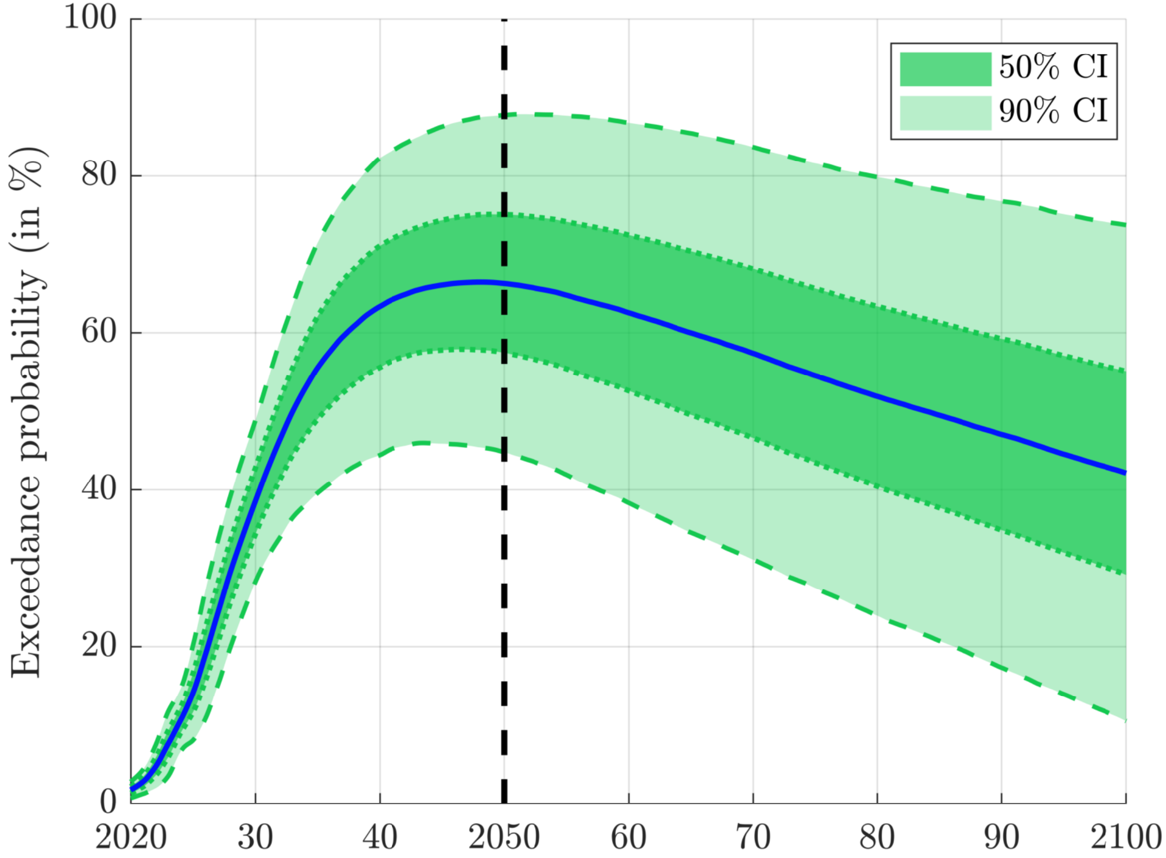


Source: `https://data.ene.iiasa.ac.at/iamc-1.5c-explorer`.

Climate scenarios

The 1.5°C scenarios

Figure 35: Confidence interval of the exceedance probability $\Pr\{\mathcal{T} > 1.5°\mathrm{C}\}$

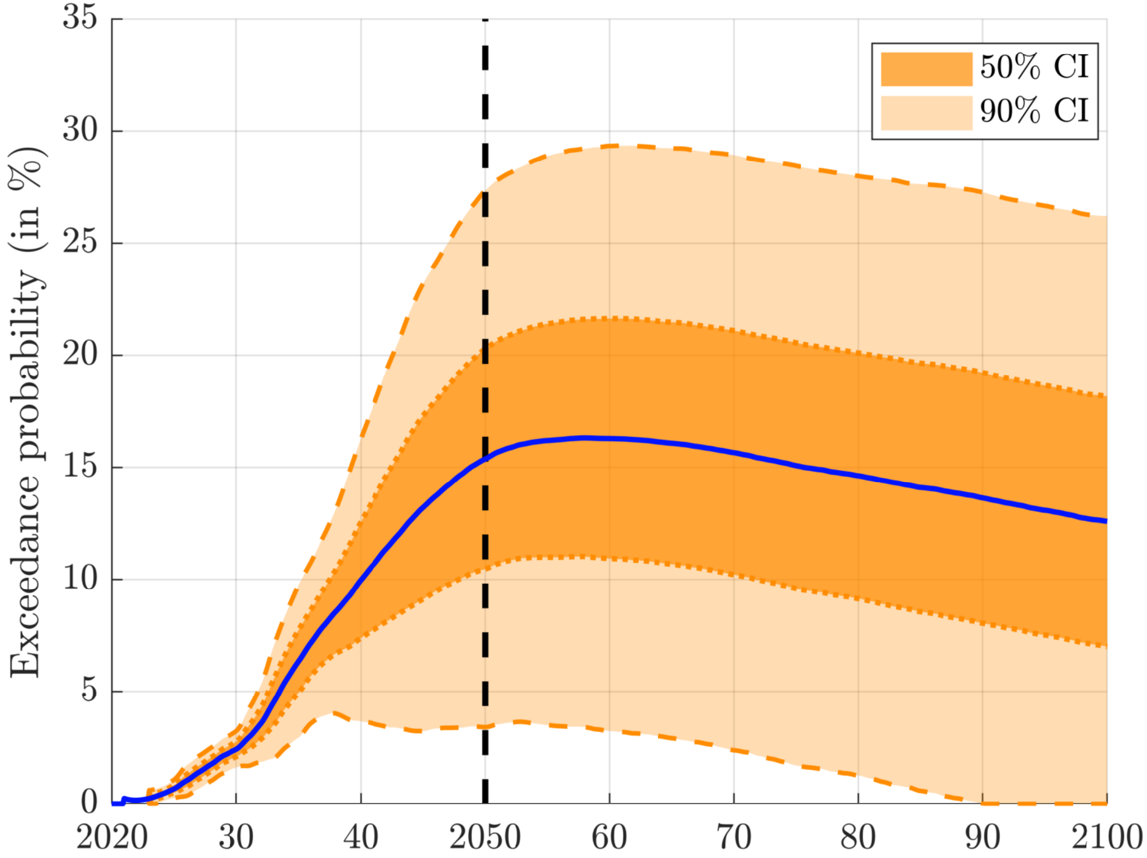


Source: `https://data.ene.iiasa.ac.at/iamc-1.5c-explorer`.

Climate scenarios

The 1.5°C scenarios

Figure 36: Confidence interval of the exceedance probability $\Pr\{\mathcal{T} > 2^{\circ}\mathrm{C}\}$



Source: `https://data.ene.iiasa.ac.at/iamc-1.5c-explorer`.

Climate scenarios

The AR6 scenarios

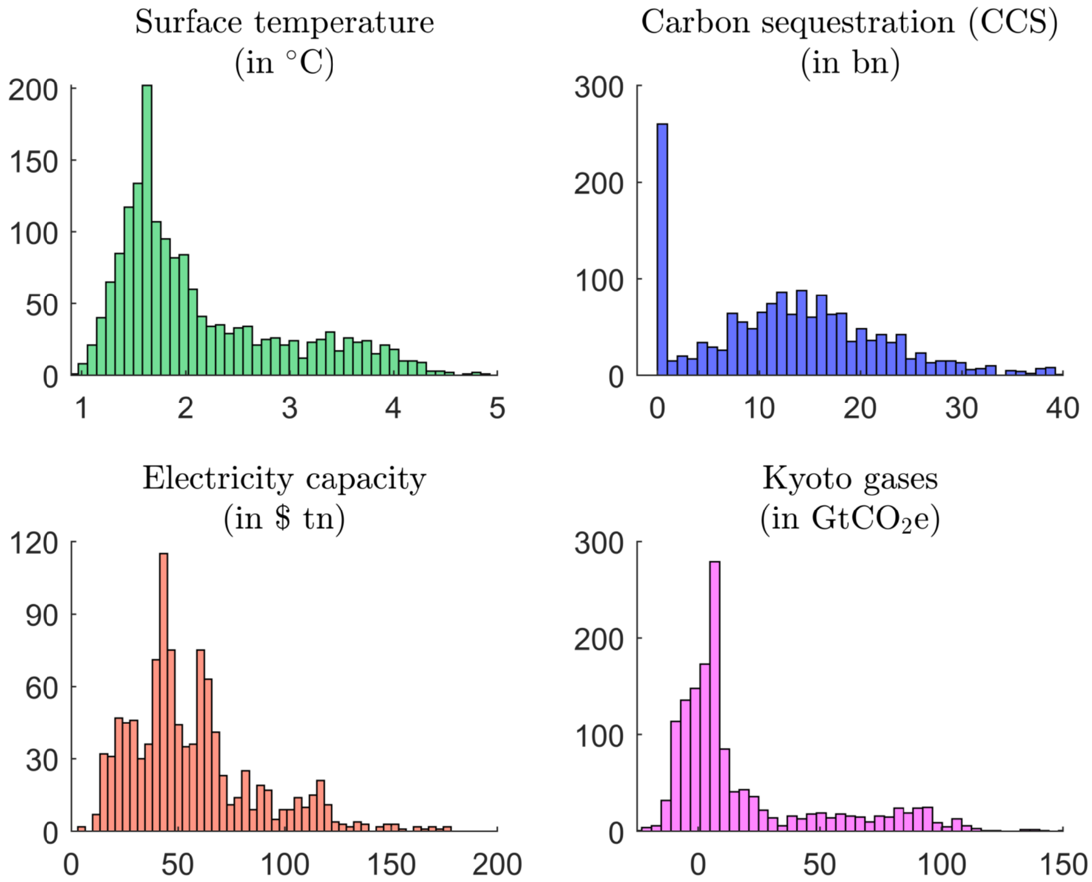
The new dataset contains 188 models, 1 389 scenarios, 244 countries and regions, and 1 791 variables, which can be split into six main categories:

- Agriculture: agricultural demand, crop, food, livestock, production, etc.
- Capital cost: coal, electricity, gas, hydro, hydrogen, nuclear, etc.
- Energy: capacity, efficiency, final energy, lifetime, OM cost, primary/secondary energy, etc.
- GHG impact: carbon sequestration, concentration, emissions, forcing, temperature, etc.
- Natural resources: biodiversity, land cover, water consumption, etc.
- Socio-economic variables: capital formation, capital stock, consumption, discount rate, employment, expenditure, export, food demand, GDP, Gini coefficient, import, inequality, interest rate, investment, labour supply, policy cost, population, prices, production, public debt, government revenue, taxes, trade, unemployment, value added, welfare, etc.

Climate scenarios

The AR6 scenarios

Figure 37: Histogram of some AR6 output variables by 2100

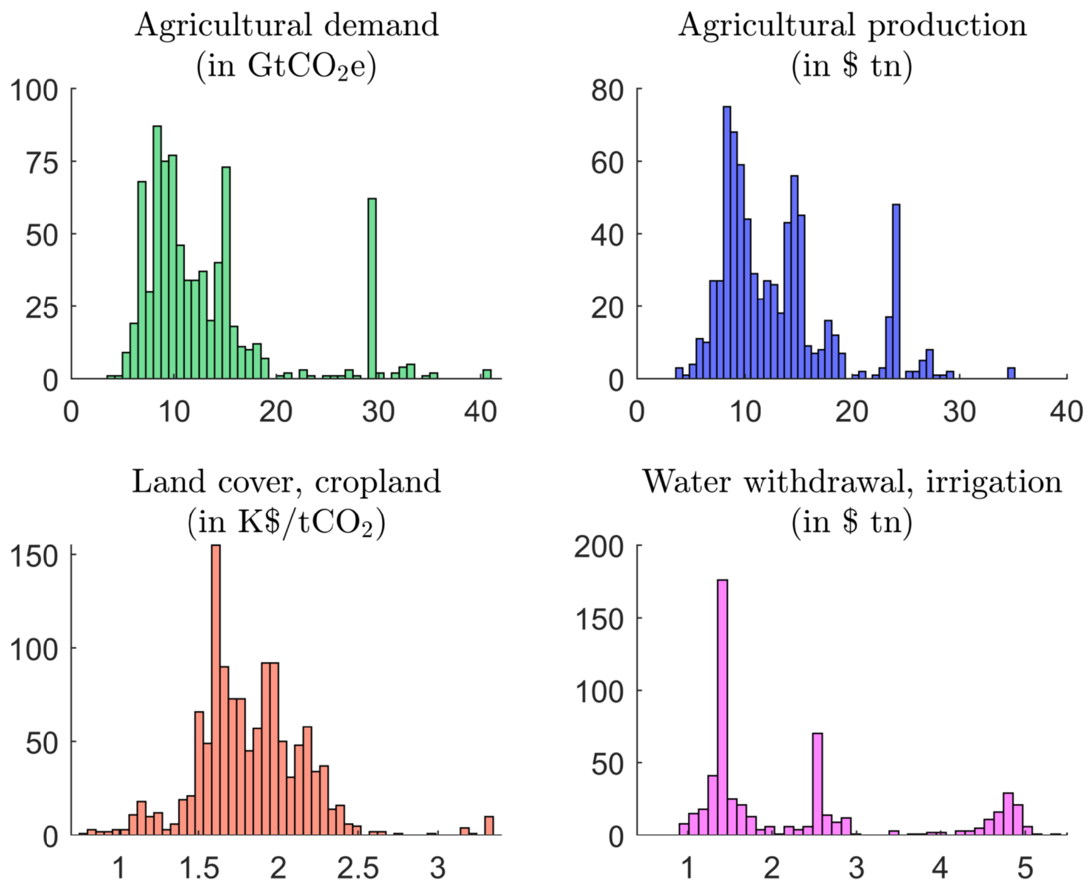


Source: https://data.ene.iiasa.ac.at/ar6.

Climate scenarios

The AR6 scenarios

Figure 38: Histogram of some AR6 output variables by 2100



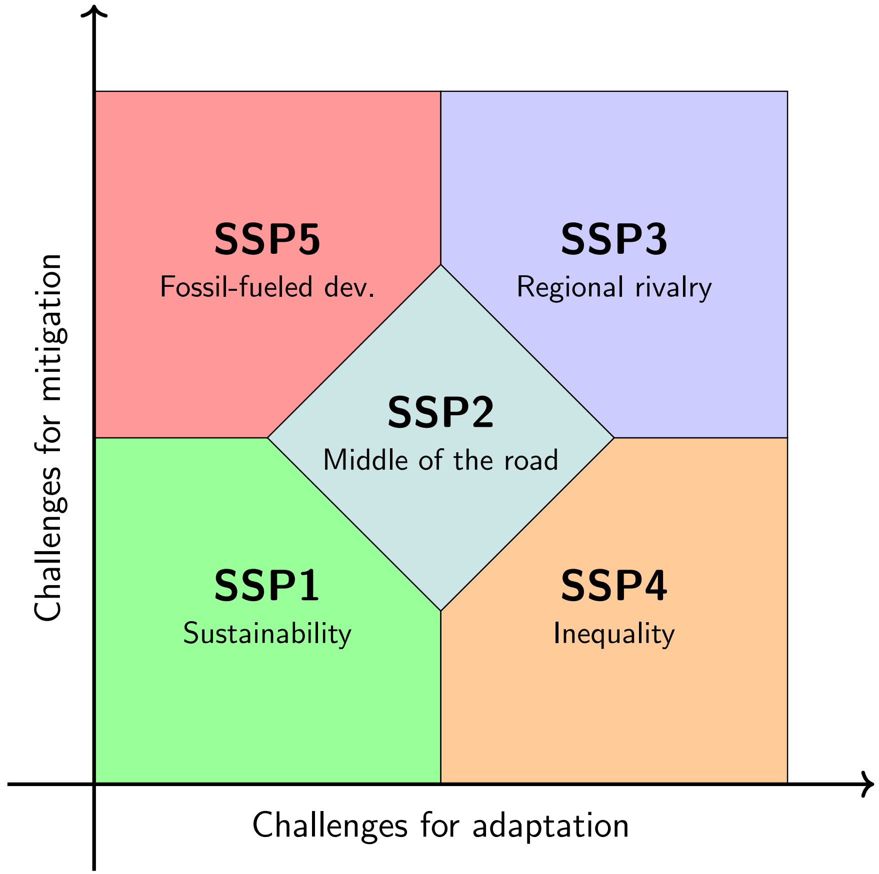
Source: `https://data.ene.iiasa.ac.at/ar6`.

Shared socioeconomic pathways

"The SSP narratives [are] a set of five qualitative descriptions of future changes in demographics, human development, economy and lifestyle, policies and institutions, technology, and environment and natural resources. [...] Development of the narratives drew on expert opinion to (1) identify key determinants of the challenges [to mitigation and adaptation] that were essential to incorporate in the narratives and (2) combine these elements in the narratives in a manner consistent with scholarship on their inter-relationships. The narratives are intended as a description of plausible future conditions at the level of large world regions that can serve as a basis for integrated scenarios of emissions and land use, as well as climate impact, adaptation and vulnerability analyses." (O'Neill et al., 2017)

Shared socioeconomic pathways

Figure 39: The shared socioeconomic pathways



Source: O'Neill *et al.* (2017).

Shared socioeconomic pathways

Figure 40: The shared socioeconomic pathways

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

Source: O'Neill *et al.* (2017).

Shared socioeconomic pathways

Relationship with the ESG dimensions

E The mitigation/adaptation trade-off is obviously an environmental issue, but the SSPs encompass other environmental narratives, e.g. land use, energy efficiency and green economy

S The social dimension is the central theme of SSPs, and concerns demography, wealth, inequality & poverty, health, education, employment, and more generally the evolution of society. This explains that SSPs and SDGs are highly interconnected

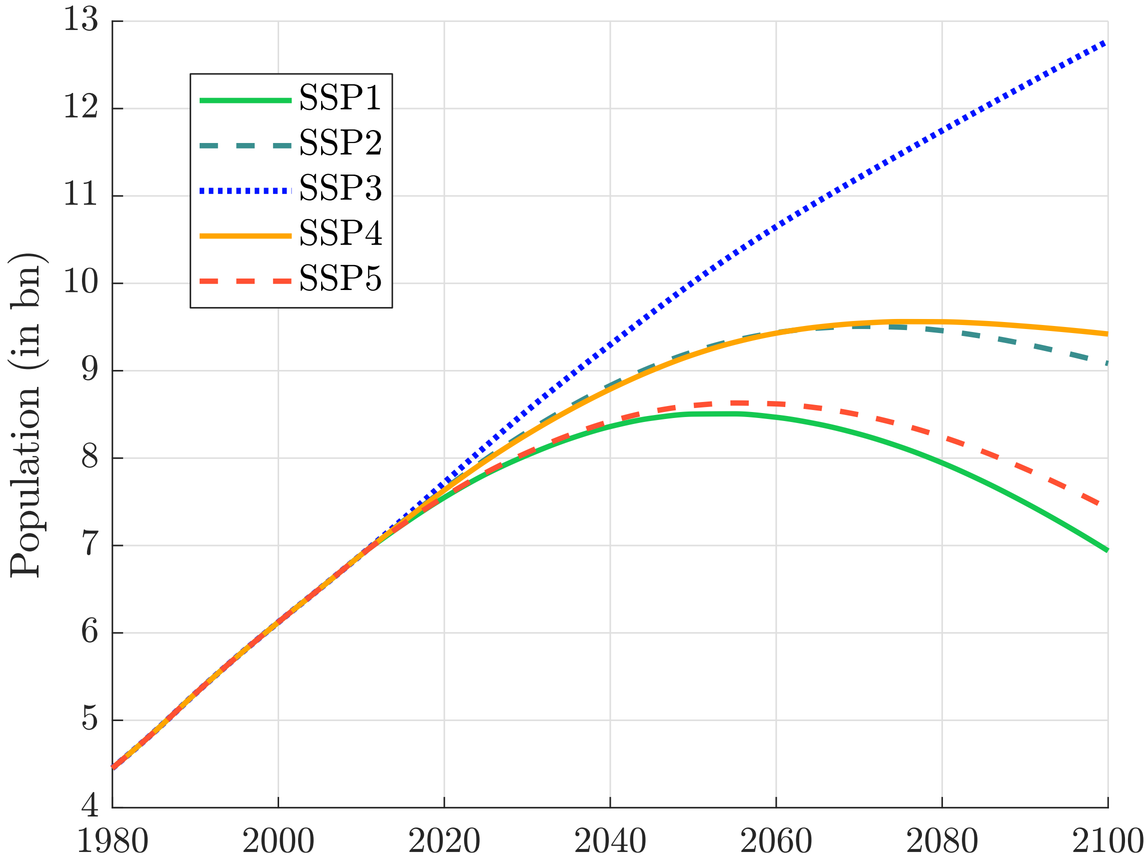
G Finally, the governance dimension is present though two major themes: international fragmentation or cooperation, and the political/economic system, including corruption, stability, rule of law, etc.

Shared socioeconomic pathways

- SSP1: IMAGE (PBL)
- SSP2: MESSAGE-GLOBIOM (IIASA)
- SSP3: AIM/CGE (NIES)
- SSP4: GCAM (PNNL)
- SSP5: REMIND-MAGPIE (PIK) and WITCH-GLOBIOM (FEEM)

Shared socioeconomic pathways

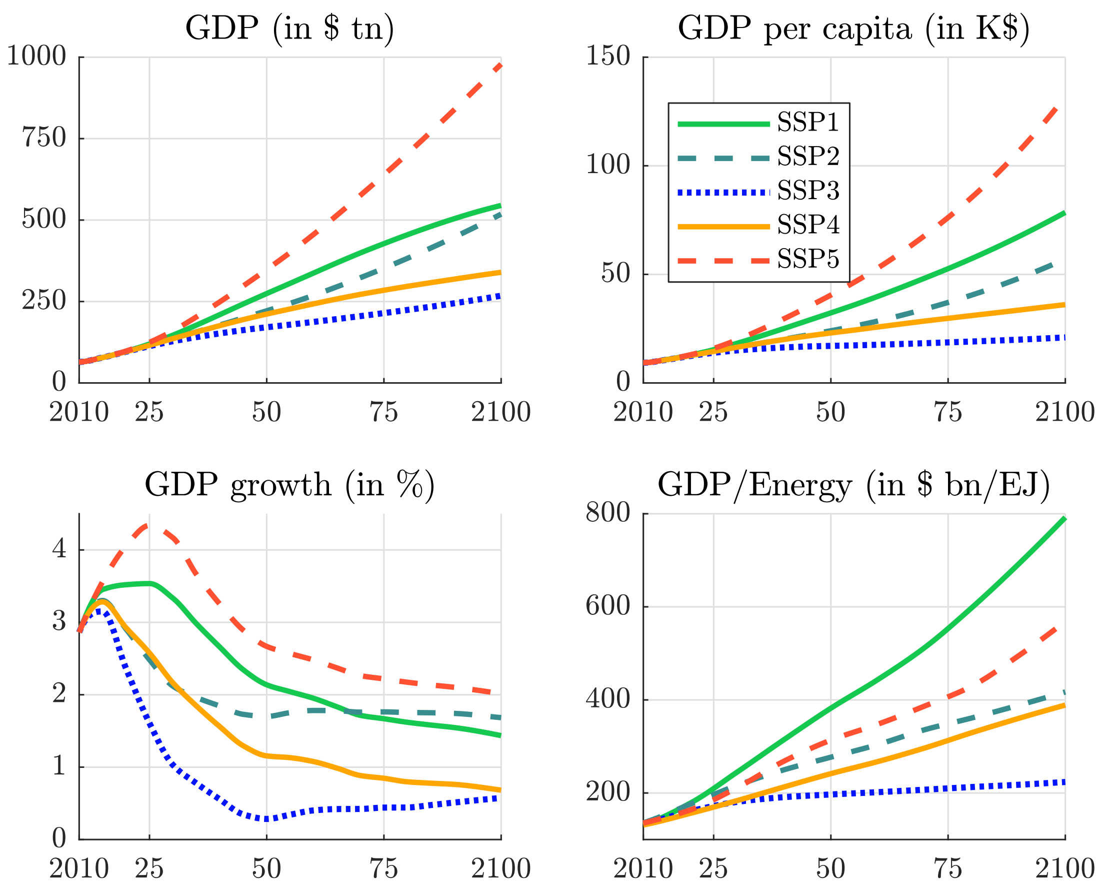
Figure 41: SSP demography projections



Source: `https://tntcat.iiasa.ac.at/SspDb`.

Shared socioeconomic pathways

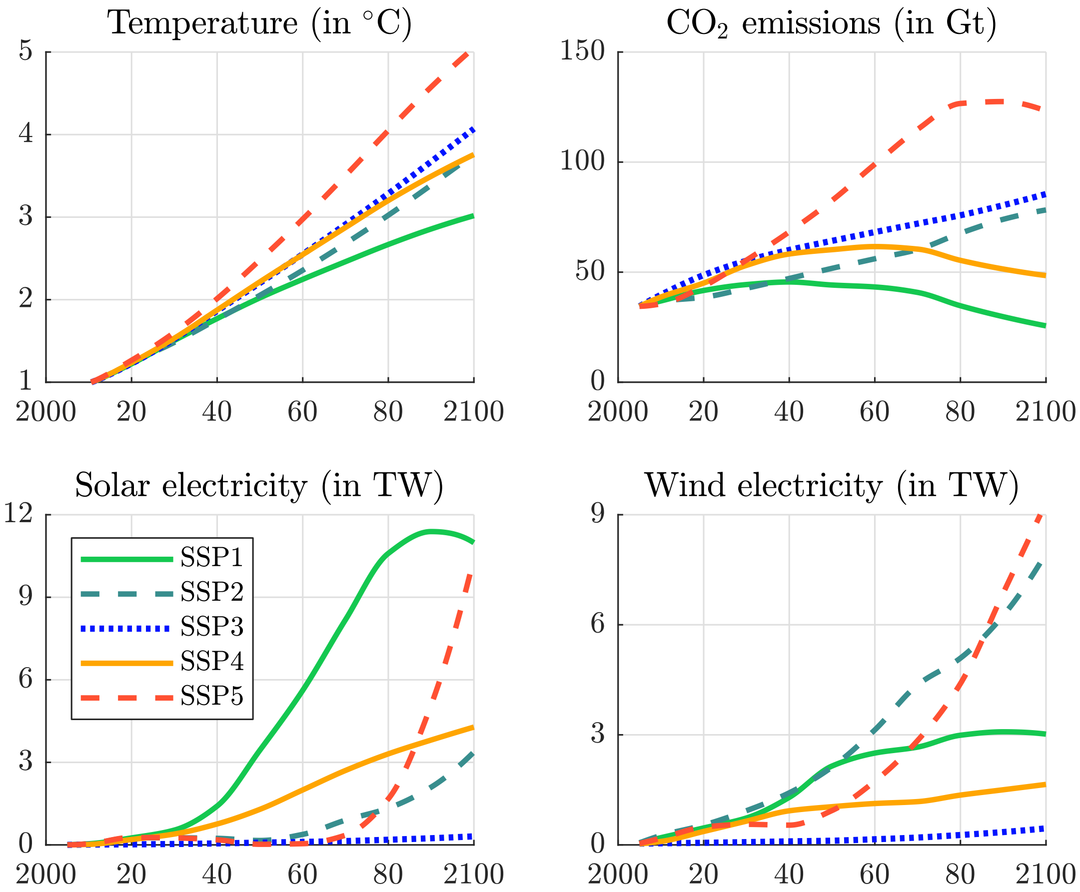
Figure 42: SSP economic projections



Source: `https://tntcat.iiasa.ac.at/SspDb`.

Shared socioeconomic pathways

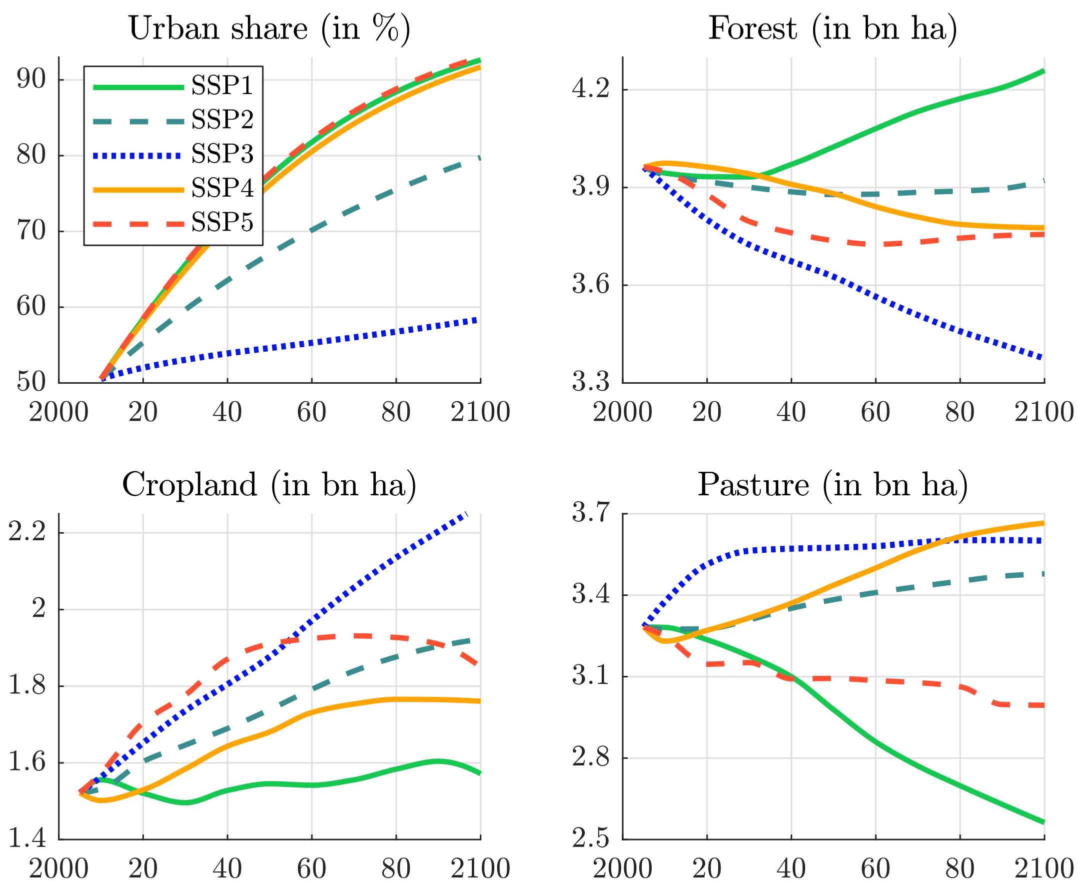
Figure 43: SSP environmental projections



Source: `https://tntcat.iiasa.ac.at/SspDb`.

Shared socioeconomic pathways

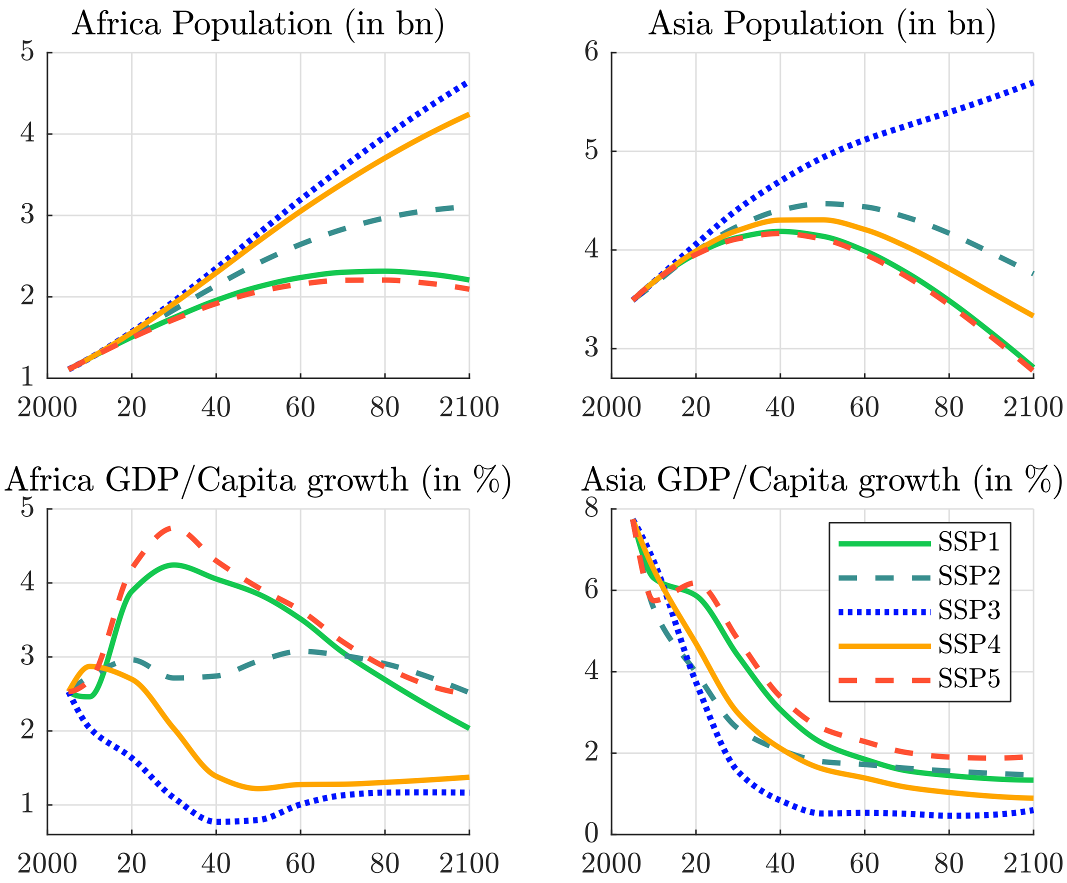
Figure 44: SSP land use projections



Source: `https://tntcat.iiasa.ac.at/SspDb`.

Shared socioeconomic pathways

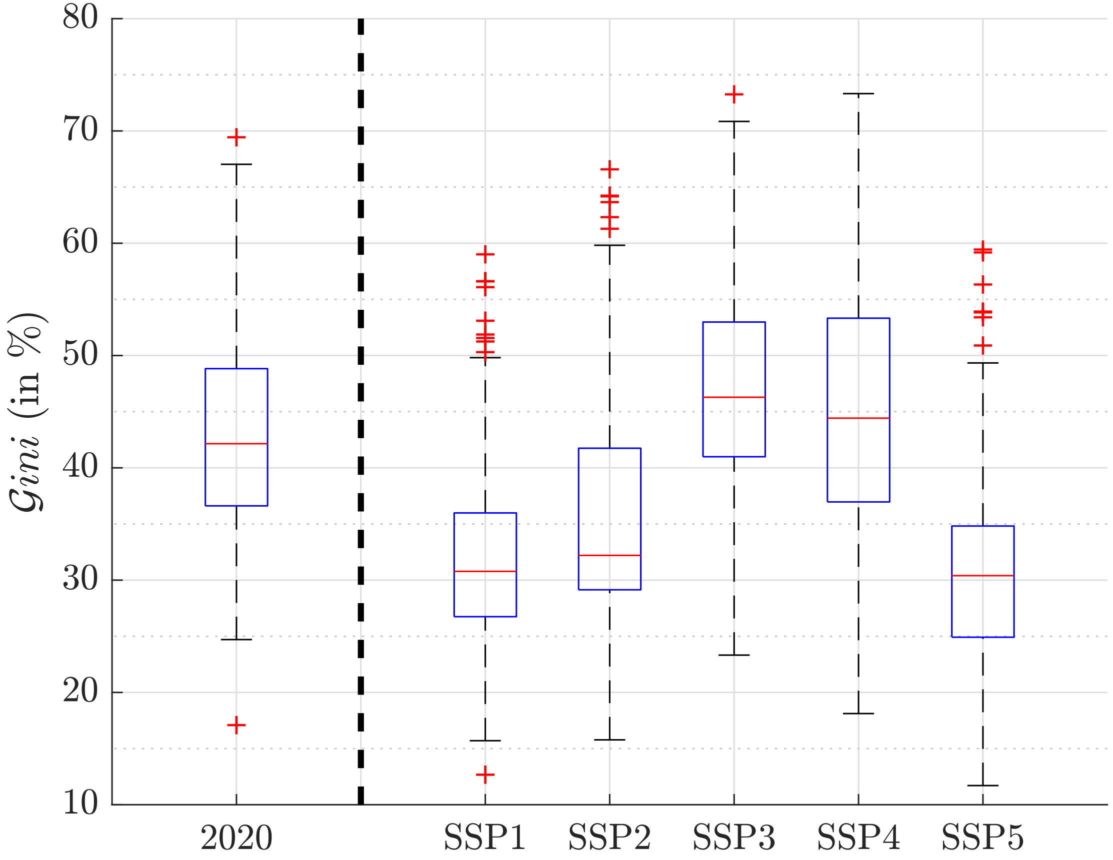
Figure 45: Example of SSP regional differences



Source: `https://tntcat.iiasa.ac.at/SspDb`.

Shared socioeconomic pathways

Figure 46: Gini coefficient projections by 2100



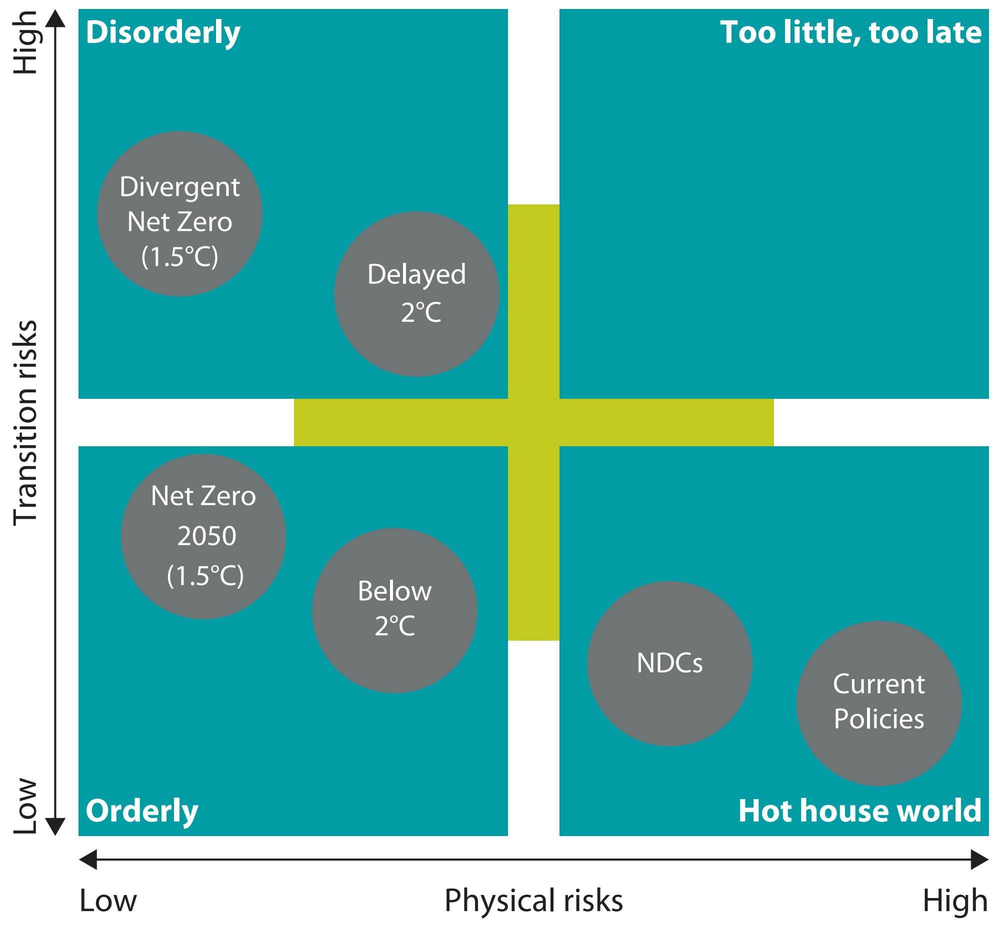
Source: `https://tntcat.iiasa.ac.at/SspDb`.

NGFS scenarios

Figure 47: Network of Central Banks and Supervisors for Greening the Financial System (NGFS)

NGFS scenarios

Figure 48: NGFS scenarios framework



NGFS scenarios

- Orderly scenarios
  - #1 Net zero 2050 (NZ)
  - #2 Below $2^{\circ}\mathrm{C}$ (B2D)
- Disorderly scenarios
  - #3 Divergent net zero (DNZ)
  - #4 Delayed transition (DT)
- Hot house world scenarios
  - #5 Nationally determined contributions (NDC)
  - #6 Current policies (CP)

NGFS scenarios

Figure 49: Physical and transition risk level of NGFS scenarios

		Physical risk	Transition risk			
Category	**Scenario**	**Policy ambition**	**Policy reaction**	**Technology change**	**Carbon dioxide removal** –	**Regional policy variation** +
Orderly	Net Zero 2050	1.4°C	Immediate and smooth	Fast change	Medium-high use	Medium variation
	Below 2°C	1.6°C	Immediate and smooth	Moderate change	Medium-high use	Low variation
Disorderly	Divergent Net Zero	1.4°C	Immediate but divergent across sectors	Fast change	Low-medium use	Medium variation
	Delayed Transition	1.6 °C	Delayed	Slow / Fast change	Low-medium use	High variation
Hot house world	Nationally Determined Contributions (NDCs)	2.6°C	NDCs	Slow change	Low-medium use	Medium variation
	Current Policies	3°C +	Non-currente policies	Slow change	Low use	Low variation

NGFS scenarios

Variables (economic)

- Central bank intervention rate
- Domestic demand
- Effective exchange rate
- Exchange rate
- Exports (goods and services)
- Gross Domestic Product (GDP)
- Gross domestic income
- Imports (goods and services)
- Inflation rate
- Long term & real interest rates
- Trend output for capacity utilisation
- Unemployment

Variables (energy)

- Coal price
- Gas price
- Oil price
- Quarterly consumption of coal
- Quarterly consumption of gas
- Quarterly consumption of oil
- Quarterly consumption of renewables
- Total energy consumption

Models (IPCC)

- Meta-model: NiGEM 1.21
- Sub-models:
  1. GCAM 5.3
  2. MESSAGE-GLOBIOM 1.1
  3. REMIND-MAgPIE 2.1-4.2

6 scenarios

1. Net Zero 2050 (NZ)
2. Below 2°C (B2D)
3. Divergent Net Zero (DNZ)
4. Delayed Transition (DT)
5. Notionally Determined Contribution (NDC)
6. Current Policies (CP)

NGFS scenarios

Table 6: Impact of climate change on the GDP loss by 2050 (GCAM)

Risk	B2D	CP	DNZ	DT	NDC	NZ
Chronic physical risk	−3.09	−5.64	−2.35	−3.28	−5.15	−2.56
Transition risk	−0.75		−3.66	−1.78	−0.89	−0.88
Combined risk	−3.84	−5.64	−6.00	−5.05	−6.03	−3.44
Combined + business confidence			−6.03	−5.09		

NGFS scenarios

Table 7: Impact of climate change on the GDP loss by 2050 (MESSAGEix-GLOBIOM)

Risk	B2D	CP	DNZ	DT	NDC	NZ
Chronic physical risk	−2.05	−5.26	−1.55	−2.64	−4.78	−1.59
Transition risk	−1.46		−10.00	−10.77	−1.39	−3.26
Combined risk	−3.51	−5.26	−11.53	−13.37	−6.16	−4.84
Combined + business confidence			−11.57	−13.40		

NGFS scenarios

Table 8: Impact of climate change on the GDP loss by 2050 (REMIND-MAgPIE)

Risk	B2D	CP	DNZ	DT	NDC	NZ
Chronic physical risk	−2.24	−6.05	−1.67	−2.65	−5.41	−1.76
Transition risk	−0.78		−3.01	−1.95	−0.33	−1.46
Combined risk	−3.02	−6.05	−4.68	−4.59	−5.73	−3.21
Combined + business confidence			−4.70	−4.63		

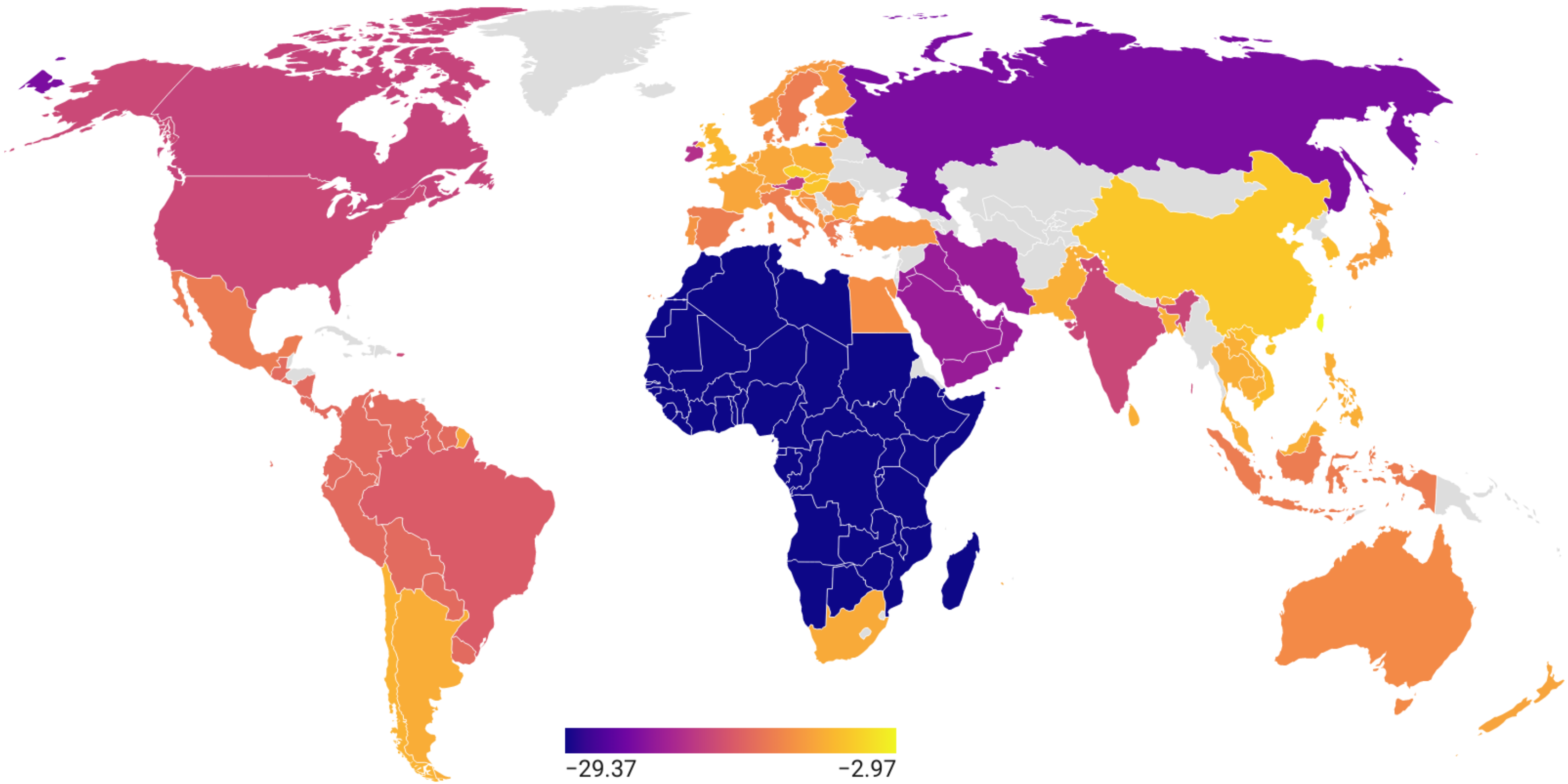
NGFS scenarios

Table 9: Impact of climate change on the GDP loss by 2050 (MESSAGEix-GLOBIOM)

Risk	B2D	CP	DNZ	DT	NDC	NZ
Africa	−13.58	−7.50	−27.35	−29.37	−11.78	−18.36
Asia	−1.50	−7.29	−5.44	−8.76	−6.78	−1.38
Australia	−4.11	−3.90	−11.03	−11.74	−5.77	−5.19
Brazil	−4.43	−5.92	−13.15	−15.90	−6.67	−6.65
Canada	−1.02	−2.37	−15.07	−18.12	−4.33	−4.87
China	−2.33	−4.97	−5.13	−6.73	−4.67	−2.76
Developing Europe	−0.28	−3.11	−0.56	−7.38	−2.73	0.39
Europe	−1.02	−2.84	−9.64	−11.02	−4.01	−1.62
France	−1.15	−2.80	−8.35	−9.48	−3.68	−1.56
Germany	−0.77	−2.38	−8.58	−9.38	−3.63	−1.21
India	−3.45	−8.61	−16.43	−17.74	−8.71	−3.86
Italy	−0.15	−3.69	−9.23	−12.88	−4.85	−0.89
Japan	−1.26	−4.14	−7.16	−10.05	−4.61	−1.40
Latam	−4.35	−6.10	−12.70	−14.58	−6.97	−5.74
Middle East	−9.97	−7.98	−22.03	−21.96	−10.28	−15.24
Russia	−12.18	−2.26	−23.46	−23.80	−7.54	−17.11
South Africa	−2.02	−5.06	−7.24	−9.16	−5.38	−3.04
South Korea	0.11	−3.49	−3.23	−7.57	−3.33	0.12
Spain	−2.41	−3.81	−12.49	−12.89	−5.41	−3.30
Switzerland	2.32	−2.25	−9.47	−10.35	−2.18	2.30
United Kingdom	−0.86	−1.90	−6.50	−8.05	−2.56	−1.33
United States	−2.67	−4.38	−15.37	−17.66	−6.31	−4.36
World	−3.51	−5.26	−11.53	−13.37	−6.16	−4.84

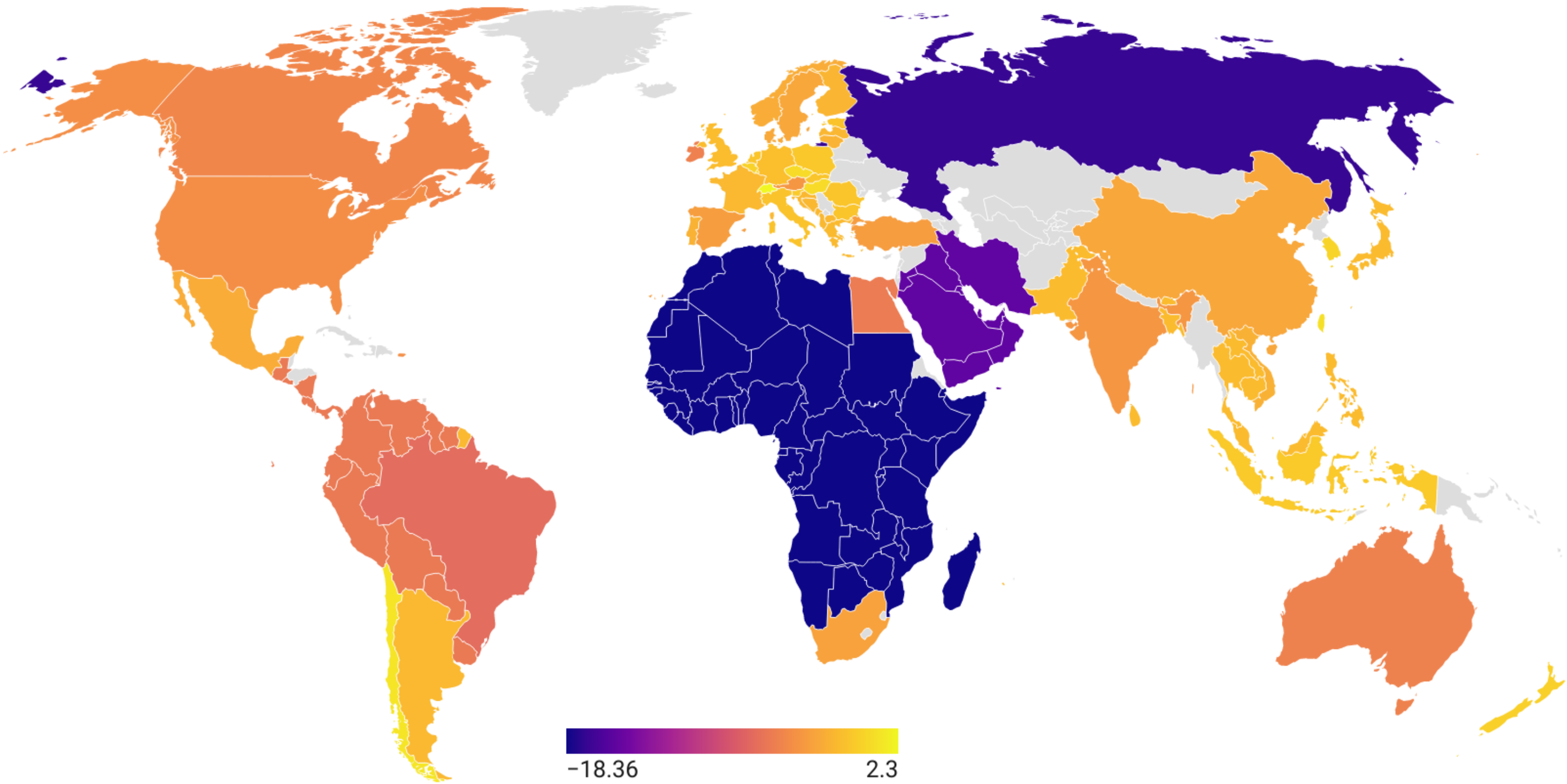
NGFS scenarios

Figure 50: GDP impact by 2050 (% change from baseline) — Delayed transition scenario



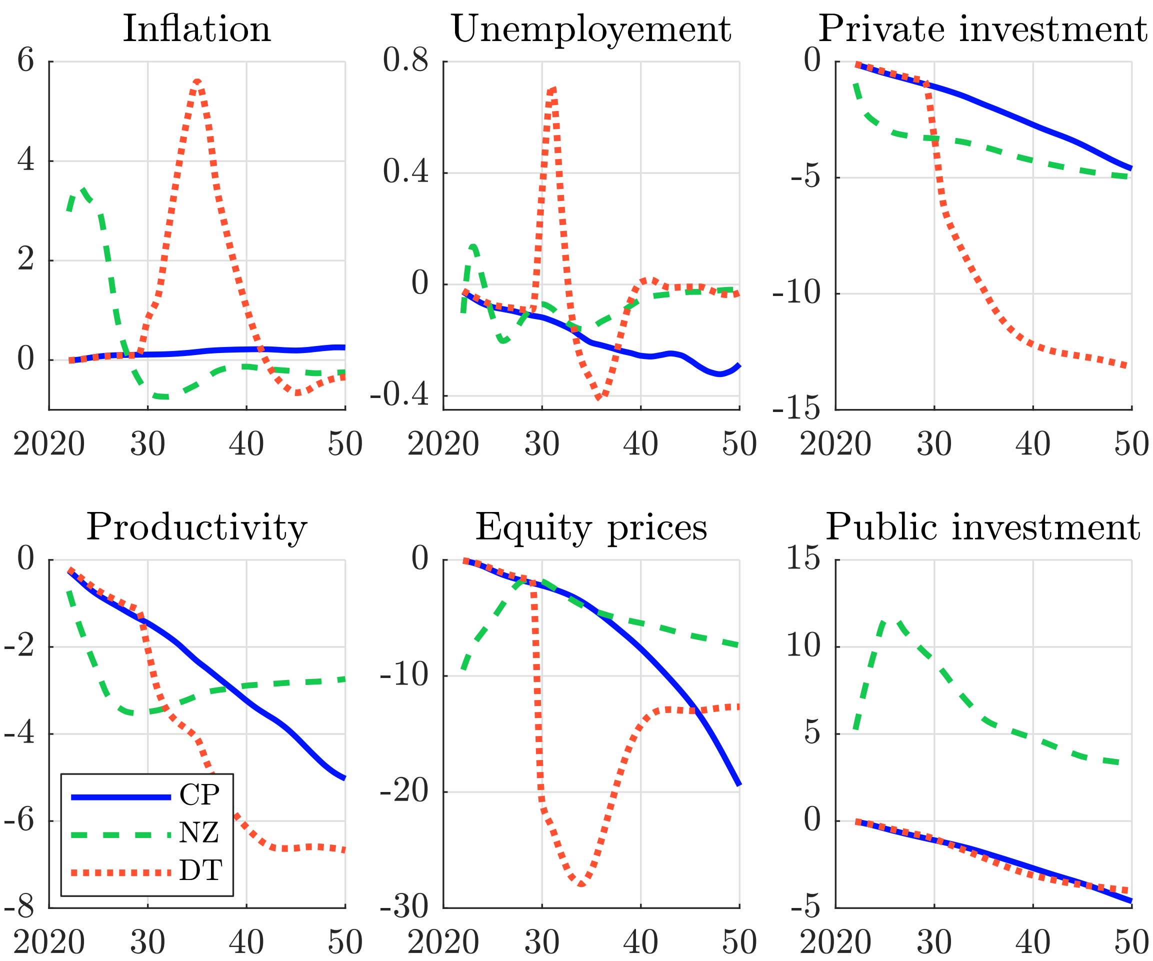
NGFS scenarios

Figure 51: GDP impact by 2050 (% change from baseline) — Net zero 2050 scenario



NGFS scenarios

Figure 52: Impact of climate scenarios on economics (% change from baseline) — China



NGFS scenarios

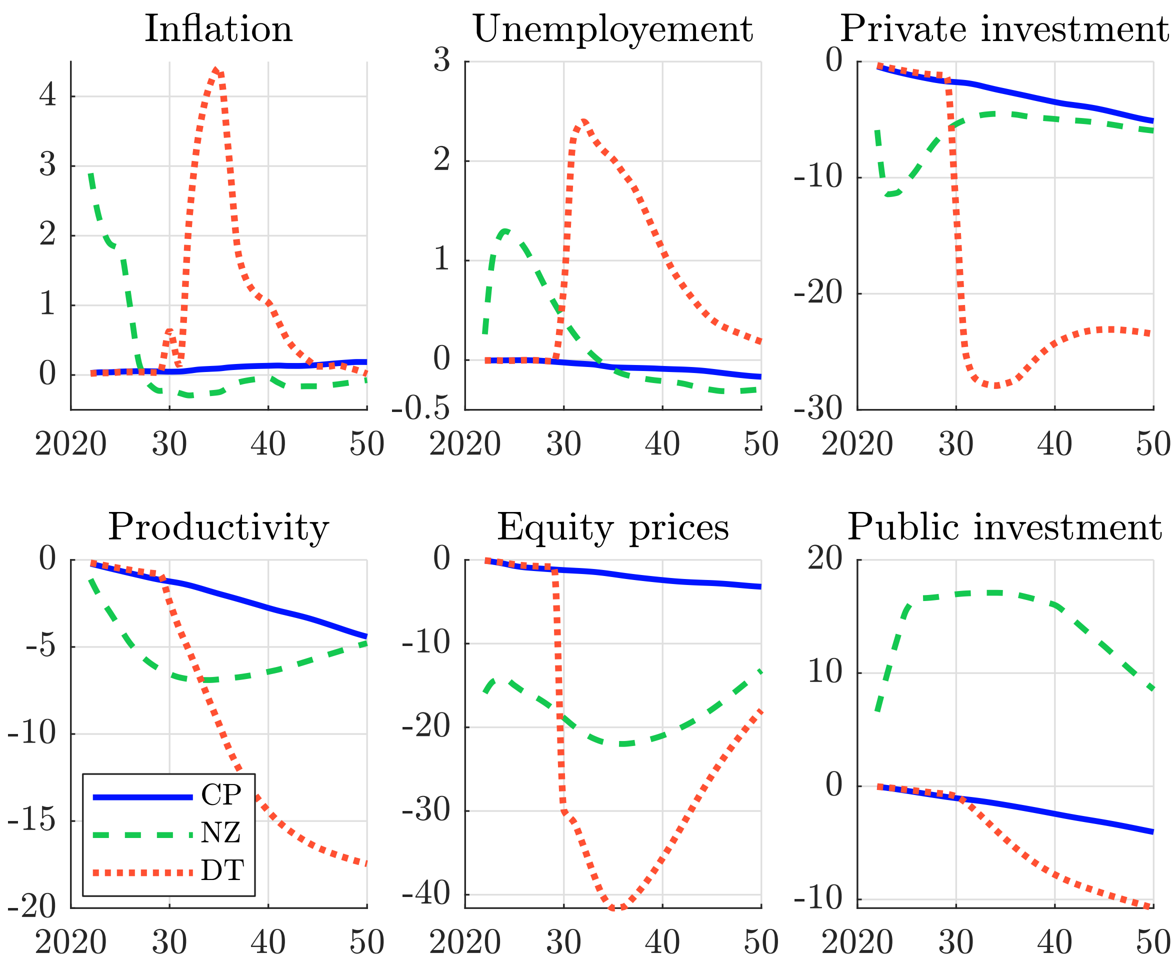
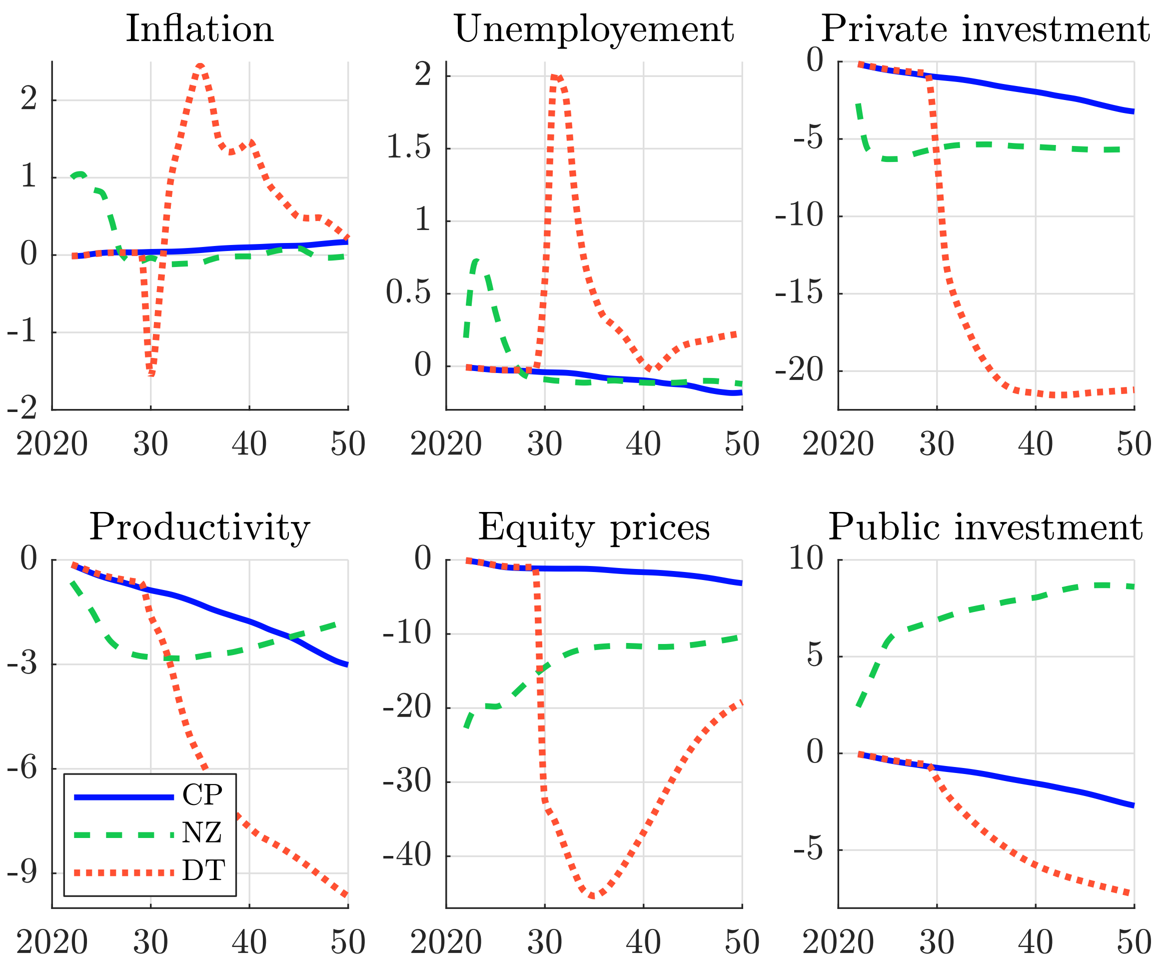


Figure 53: Impact of climate scenarios on economics (% change from baseline) — United States

NGFS scenarios

Figure 54: Impact of climate scenarios on economics (% change from baseline) — France



NGFS scenarios

Figure 55: Impact of climate scenarios on economics (% change from baseline) — United Kingdom