NAVIGATE Summer School 2023

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Exploring uncertainty

with IAMs and scenarios

Picture by Jakub Kriz on Unsplash

Let’s start with two questions

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Let’s start with two questions

- What uncertain factors have the most influence on your results?
    1. Population
    2. Economic activity
    3. Climate change impacts
    4. (Energy) demand
    5. Technology parameters
    6. Other…

Let’s start with two questions

- What type of uncertainty dominates for your results?
  1. Uncertainty about values of input parameter,
  2. Uncertainty about the forms of relationships represented,
  3. Uncertainty due to omitted mechanisms,
  4. Other type of uncertainty,
  5. I don’t know

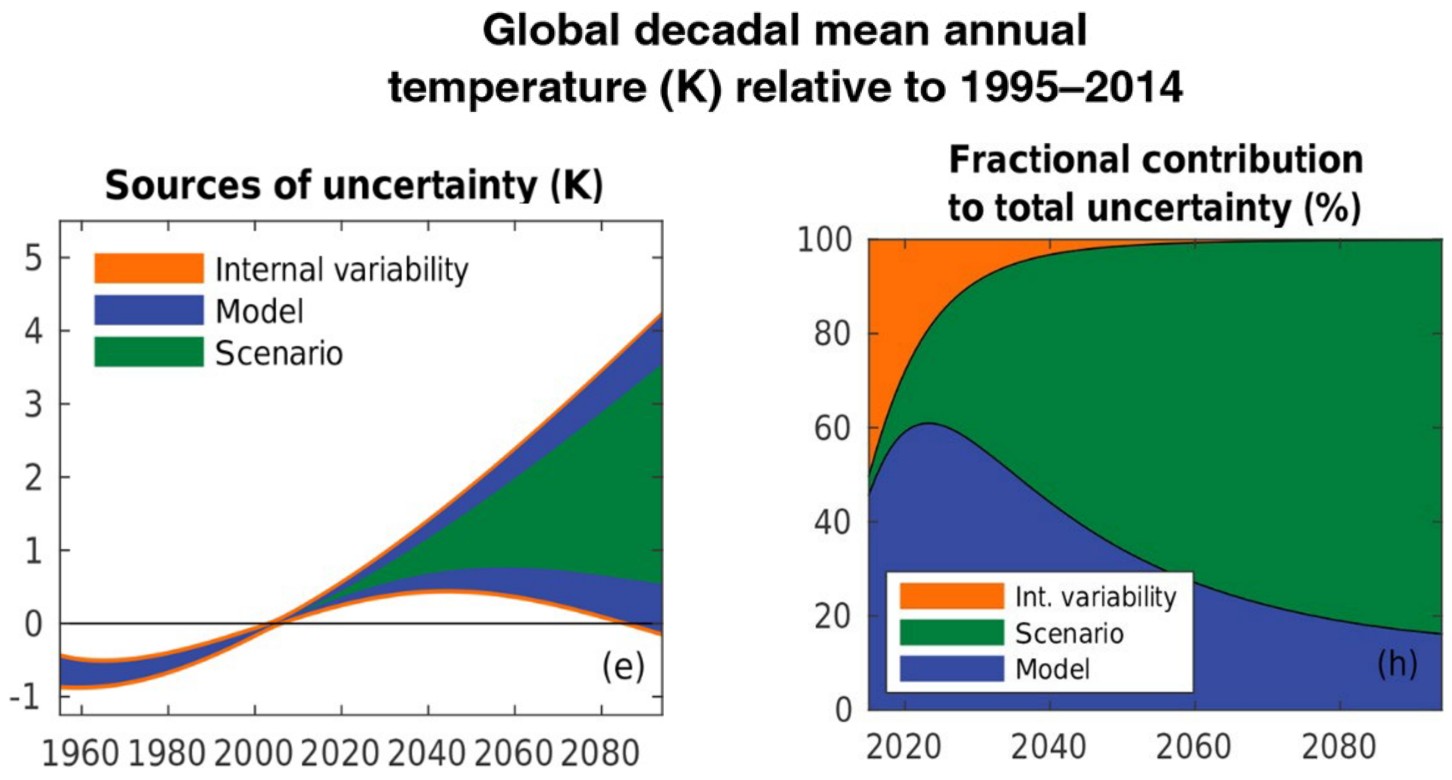

Picture by Jakub Kriz on Unsplash

1. Some frameworks to think about uncertainty and modelling

2. Some case studies

3. Some conclusive remarks

Why study the uncertainty in emissions and mitigation pathways ?



Lehner et al. 2020. “Partitioning Climate Projection Uncertainty with Multiple Large Ensembles and CMIP5/6.” Earth System Dynamics 11 (2): 491–508. doi.org/10.5194/esd-11-491-2020

Uncertainties are at the core of “post-normal science”

Four destabilising features : “facts uncertain, values in dispute, stakes high and decisions urgent”.

Whereas science was previously understood as steadily advancing in the certainty of our knowledge and control of the natural world, now science is seen as coping with many uncertainties in policy issues of risk and the environment.

Uncertainty is not banished but is managed, and values are not presupposed but are made explicit.

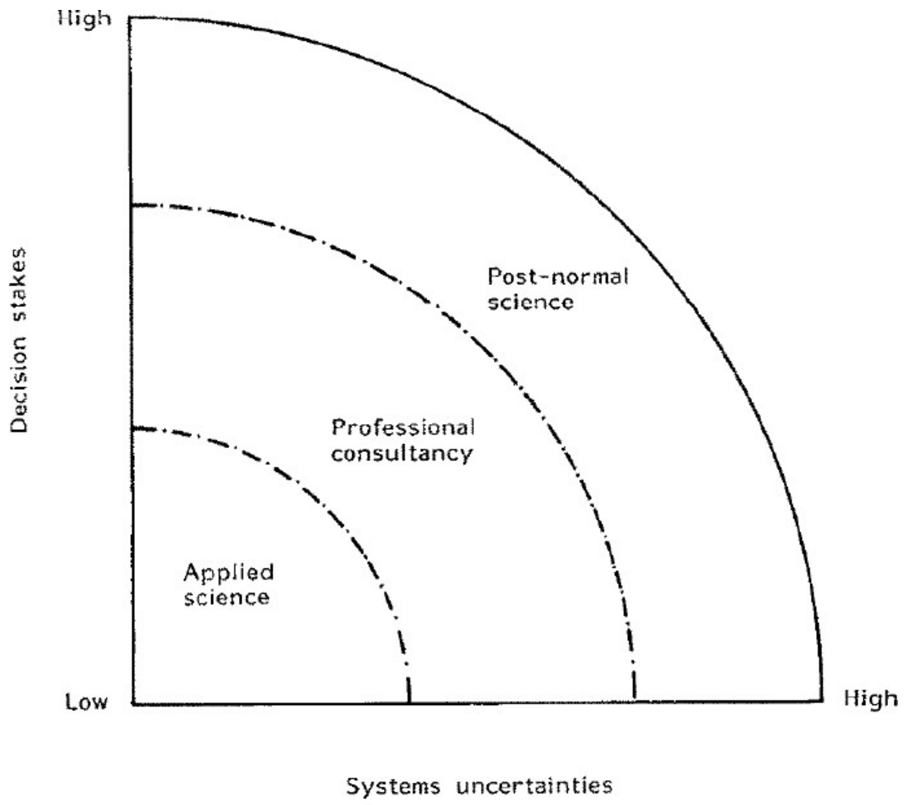


Figure 1. Problem-solving strategies

Funtowicz and Ravetz. 1992. “The Good, the True and the Post-Modern.” Futures 24 (10): 963–76. https://doi.org/10.1016/0016-3287(92)90131-X.

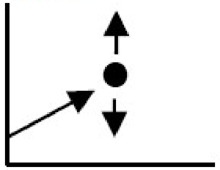
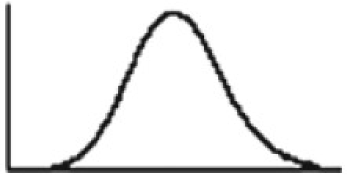
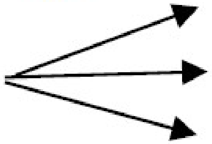
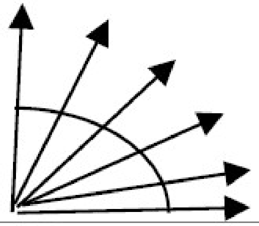
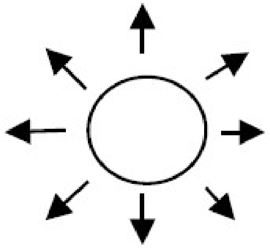
Types and sources of uncertainty

- **Scientific uncertainty**

Our knowledge about the causes, processes, and consequences of a system's evolution and outcomes is incomplete.

  - Variability, stochasticity
  - Limited knowledge

Types and sources of uncertainty

	Complete determinism	Level 1	Level 2	Level 3	Level 4 (deep uncertainty)		Total ignorance
					Level 4a	Level 4b	
Context (X)		A clear enough future 	Alternate futures (with probabilities) 	A few plausible futures 	Many plausible futures 	Unknown future 	"unknown unknowns"
System model (R)		A single (deterministic) system model	A single (stochastic) system model	A few alternative system models	Many alternative system models	Unknown system model; know we don't know	
System outcomes (O)		A point estimate for each outcome	A confidence interval for each outcome	A limited range of outcomes	A wide range of outcomes	Unknown outcomes; know we don't know	

Marchau et al. 2019. Decision Making under Deep Uncertainty: From Theory to Practice. Springer Nature.

Types and sources of uncertainty

- **Risk-type uncertainty**

Known and (perceived as) quantifiable uncertainty (objective distribution of probabilities)

  - Known *a priori* from mathematical probability (e.g.. rolling a dice)
  - Inferred from large number of observations or experiments (e.g.. observed frequency of an event)

- **Uncertainty proper**

Unable to define probabilistic beliefs/to describe the known uncertainty in statistical terms. Cannot be reduced to an objective distribution of probabilities. Ambiguity.

Deep uncertainty refers to "the condition in which analysts do not know or the parties to a decision cannot agree upon

(1) the appropriate models to describe interactions among a system's variables,
(2) the probability distributions to represent uncertainty about key parameters in the models, and/or
(3) how to value the desirability of alternative outcomes" (Lempert et al. 2003)

Lempert et al. 2003. Shaping the next one hundred years: New methods for quantitative long-term strategy analysis (MR-1626-RPC). Santa Monica, CA: The RAND Pardee Center.

Types and sources of uncertainty

- **Scientific uncertainty**

Our knowledge about the causes, processes, and consequences of a system's evolution and outcomes is incomplete.

  - Variability, stochasticity
  - Limited knowledge

- **Ethical uncertainty**

It is not clear what framework(s) we should apply to value the outcomes and address the ethical questions raised by a given process or decision.

Decision making under (deep) uncertainty

- With respect to decision-making, uncertainty refers to the gap between available knowledge and the knowledge decision-makers would need in order to make the best strategy/policy choice.

- The conjunction of uncertainty and irreversibility (or inertia) is critical
  - Arrow, K. J., and A. C. Fisher. 1974. "Environmental Preservation, Uncertainty, and Irreversibility." *The Quarterly Journal of Economics*, 312–19.
  - Henry, C. 1974. "Investment Decisions under Uncertainty: The" Irreversibility Effect"." *The American Economic Review*, 1006–12.

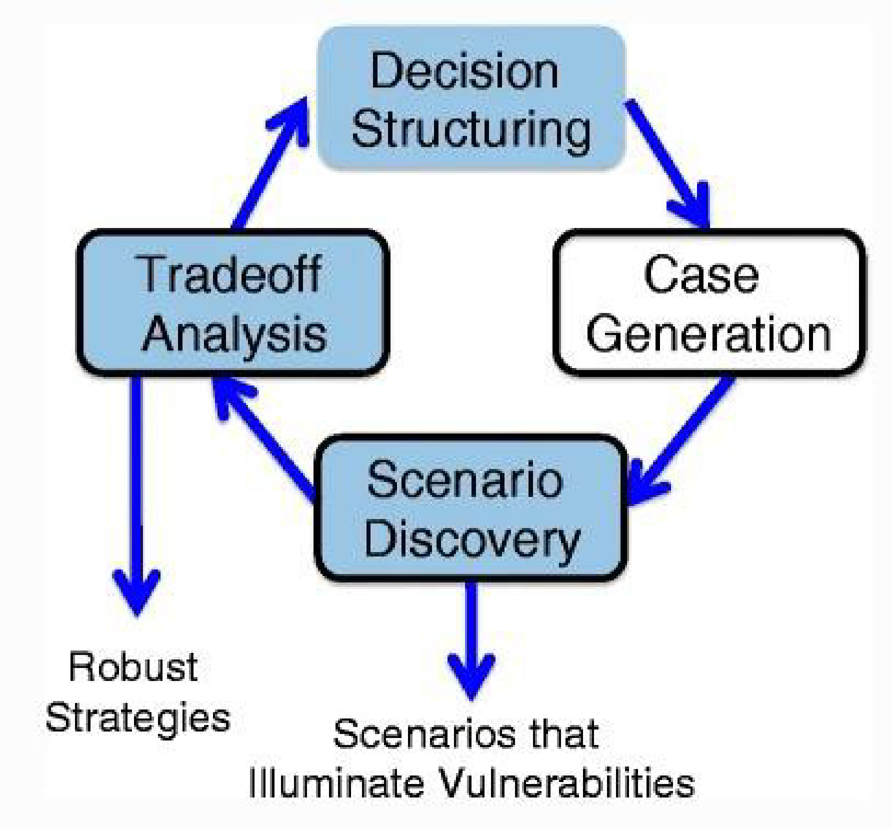
- (Deep) uncertainty often involves decisions that are made over time in dynamic interaction with the system.

- Decisions may rely on the frameworks of sequential decision, precautionary principle, or the idea to minimize regret/avoid vulnerability instead of optimizing expected result.

Robust Decision Making

Robust Decision Making (Lempert et al., 2006, 2013) is a combination of scenario planning with computing to support decision makers by helping to identify potential strategies that are robust to future unknowns, characterize the vulnerabilities of such strategies, and evaluate tradeoffs among alternatives.

In this context, the vulnerabilities of a strategy are the combinations of uncertainties under which it performs poorly. Characterizing vulnerabilities allows for the iterative improvement of the strategy.



Lempert et al. 2006. “A General, Analytic Method for Generating Robust Strategies and Narrative Scenarios.” Management Science 52 (4): 514–28.

Lempert. 2013. “Scenarios That Illuminate Vulnerabilities and Robust Responses.” Climatic Change 117 (4): 627–46.

IAMs and uncertainty

Uncertainties in

- Model quantities [alternative values, parametric uncertainty]
- Model form (e.g. form of damage function) [alternative relationships, structural uncertainty]
- Model completeness/adequacy (e.g. omitted mechanisms, such as tipping points) [structural uncertainty]

"Salient uncertainties":

- What is (thought to be) uncertain/is the object of controversies (analysis of knowledge)
- What matters for model results (model sensitivity analysis)

Modelling choices: model scope, equations, parameter values, output presentation

van Asselt and Rotmans. 2002. "Uncertainty in Integrated Assessment Modelling." Climatic Change 54 (1): 75–105. doi.org/10.1023/A:1015783803445.

Beck and Krueger. 2016. "The Epistemic, Ethical, and Political Dimensions of Uncertainty in Integrated Assessment Modeling." WIREs: Climate Change 7 (5): 627–45. doi.org/10.1002/wcc.415.

Imaclim-R model

Demography

Labor productivity

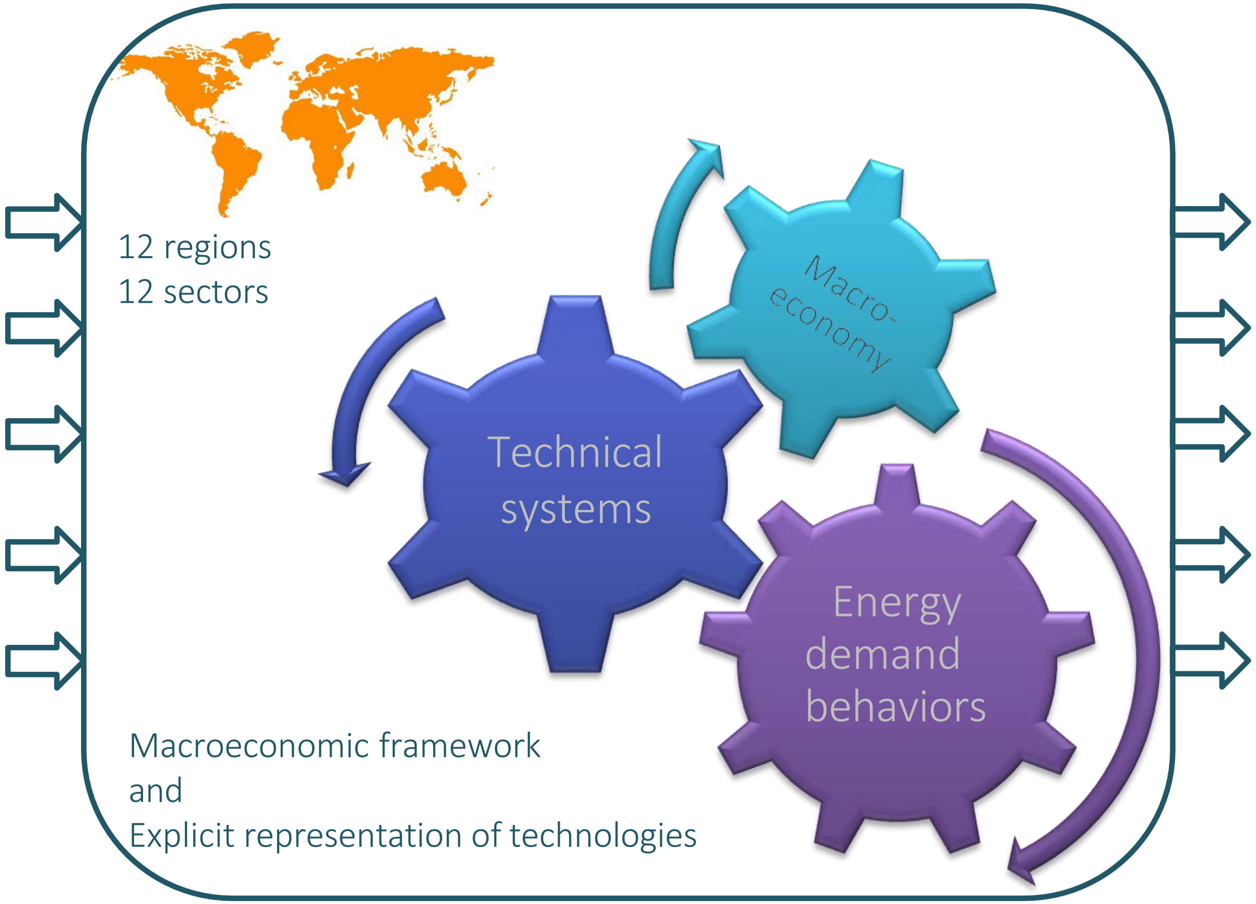
Technologies learning-rates and potentials

Fossil fuel reserves

Parameters induced energy-efficiency

Parameters of the functions representing life-styles

…



CO_2 emissions

Energy use by types and by sectors

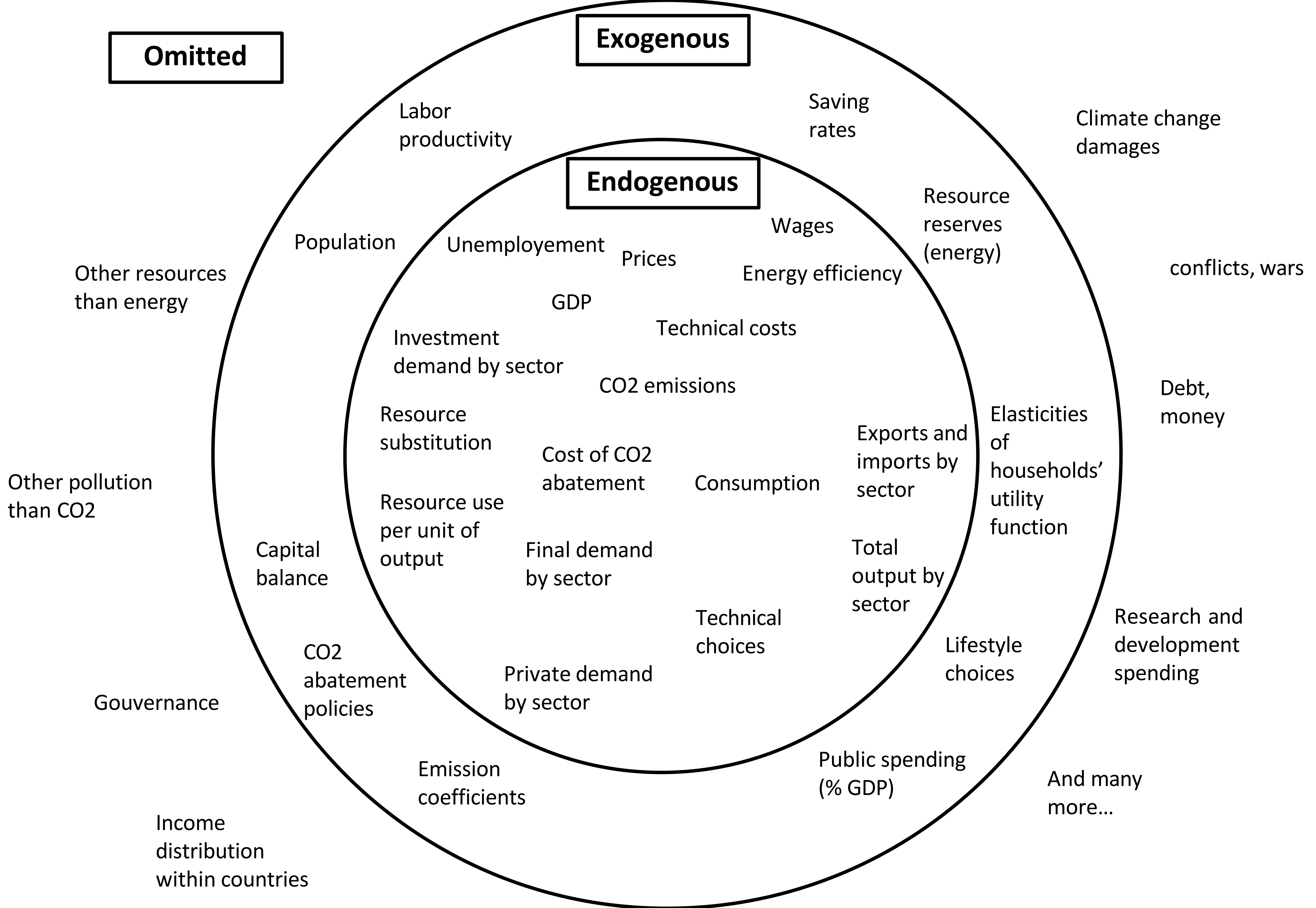
Energy prices

Technology choices

GDP and its structure

…

Waisman et al. 2012. 'The Imaclim-R Model : Infrastructures, Technical Inertia and the Costs of Low Carbon Futures under Imperfect Foresight.' Climatic Change 114 (1), 101-120.


Omitted
Exogenous
Endogenous
Labor productivity
Saving rates
Climate change damages
Resource reserves (energy)
Wages
Population
Unemployement
Prices
Energy efficiency
conflicts, wars
Other resources than energy
GDP
Technical costs
Investment demand by sector
CO2 emissions
Debt, money
Resource substitution
Elasticities of households' utility function
Exports and imports by sector
Cost of CO2 abatement
Consumption
Other pollution than CO2
Resource use per unit of output
Capital balance
Final demand by sector
Total output by sector
Technical choices
Research and development spending
CO2 abatement policies
Lifestyle choices
Private demand by sector
Gouvernance
Emission coefficients
Public spending (% GDP)
And many more…
Income distribution within countries


Picture by Jakub Kriz on Unsplash

1. Some frameworks to think about uncertainty and modelling

2. Some case studies

3. Some take home messages

An example with both “scientific” and “ethical” uncertainty

Taconet, Nicolas, Céline Guivarch, and Antonin Pottier. 2021. “Social Cost of Carbon Under Stochastic Tipping Points.” *Environmental and Resource Economics* 78 (4): 709–37. https://doi.org/10.1007/s10640-021-00549-x

RESEARCH QUESTIONS

- How does the possibility of a tipping-point in impact from climate change influence the Social Cost of Carbon?
- What is the effect of pure risk and risk aversion?

METHODS

- Stochastic Cost-benefit Integrated Assessment Model (Guivarch and Pottier, 2018)
- Isolating the effect of risk:
  - Disentangle *risk* and *time* preferences (Epstein-Zin)

<u>Social welfare</u>

Under expected utilitarianism with Constant Relative Risk Aversion

$$U_t = \left(1 - \frac{1}{1+\rho}\right)u_t + \frac{1}{1+\rho}\mathbb{E}[U_{t+1}]$$

Under an Epstein–Zin social welfare function

$$U_t = \left(\left(1 - \frac{1}{1+\rho}\right)u_t + \frac{1}{1+\rho}\mathbb{E}[U_{t+1}^{1-\gamma}]^{\frac{1-\theta}{1-\gamma}}\right)^{\frac{1}{1-\theta}}$$

utility at each time step : $u_t = L_t \dfrac{(C_t/L_t)^{1-\theta}}{1-\theta}$

Resarch questions

- How does the possibility of a tipping-point in impact from climate change influence the Social Cost of Carbon?
- What is the effect of pure risk and risk aversion?

Methods

- Stochastic Cost-benefit Integrated Assessment Model (Guivarch and Pottier, 2018)
- Isolating the effect of risk:
  - Disentangle *risk* and *time* preferences (Epstein-Zin)
  - Controling for expected damage

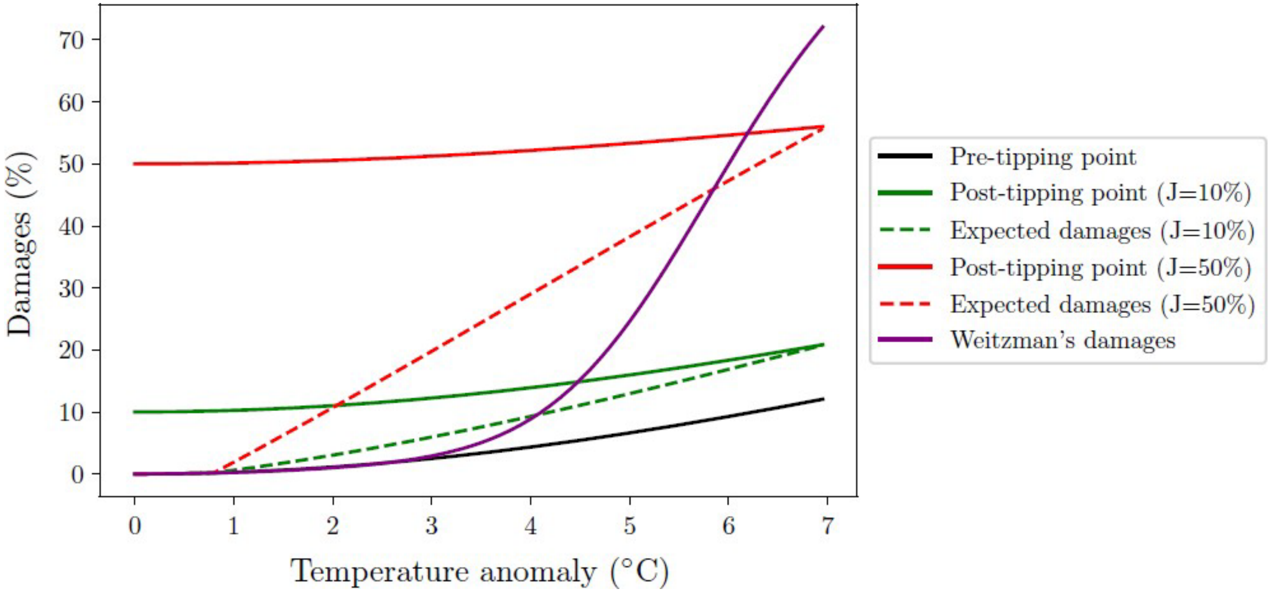
Damage factor

Before tipping: $$\Omega_1(T) = \frac{1}{1+\pi T^2}$$

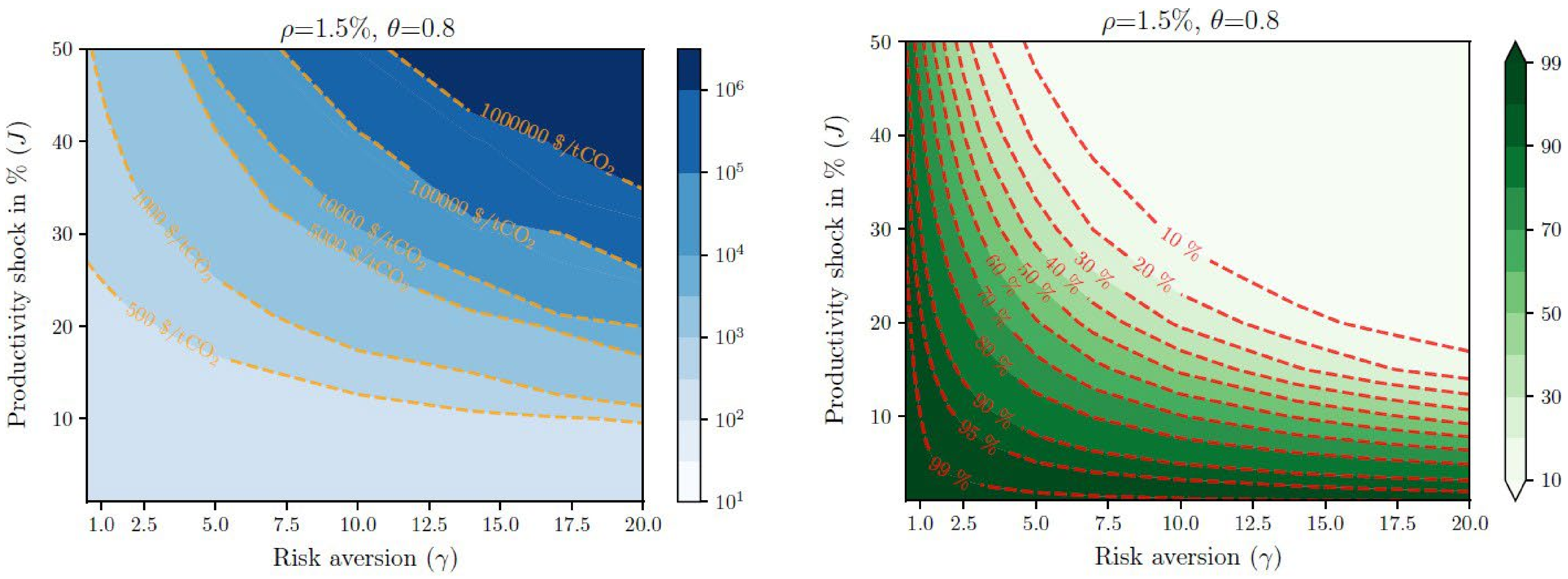
After tipping: $$\Omega_2(T) = \frac{1-J}{1+\pi T^2}$$

Probability to reach tipping point :

$$h_t(T_t, T_{t-1}) = \begin{cases} 0 & \text{if } T_t \leq T_{t-1} \text{ or } T_t \leq T_{\min} \\ \frac{T_t - \max(T_{\min}, T_{t-1})}{T_{\max} - \max(T_{\min}, T_{t-1})} & \text{if } T_t > T_{t-1} \text{ and } T_{\min} \leq T_t \leq T_{\max} \\ 1 & \text{if } T_t > T_{t-1} \text{ and } T_t \geq T_{\max} \end{cases}$$



How does the possibility of a tipping-point in impact from climate change influence the Social Cost of Carbon?



(a) **(b)**

Comparison of the Social Cost of Carbon to a risk-free SCC under expected damages for Epstein-Zin preferences: Heatmap of the Social Cost of Carbon (**a** in US$2005) and the share of its value that can be explained by expected damages (**b** ratio SCC_{ed} / SCC).


Picture by Jakub Kriz on Unsplash

Exploring emissions and mitigation pathways when many parameters and trends are uncertain

Two examples with one IAM and an ensemble of scenarios

Guivarch, Céline, Julie Rozenberg, and Vanessa Schweizer. 2016. “The Diversity of Socio-Economic Pathways and CO2 Emissions Scenarios: Insights from the Investigation of a Scenarios Database.” *Environmental Modelling & Software* 80: 336–53. https://doi.org/10.1016/j.envsoft.2016.03.006.

Rozenberg, Julie and Céline Guivarch. “GDP losses and GDP levels associated with mitigation pathways: main sources of uncertainty”. Not (yet) published.

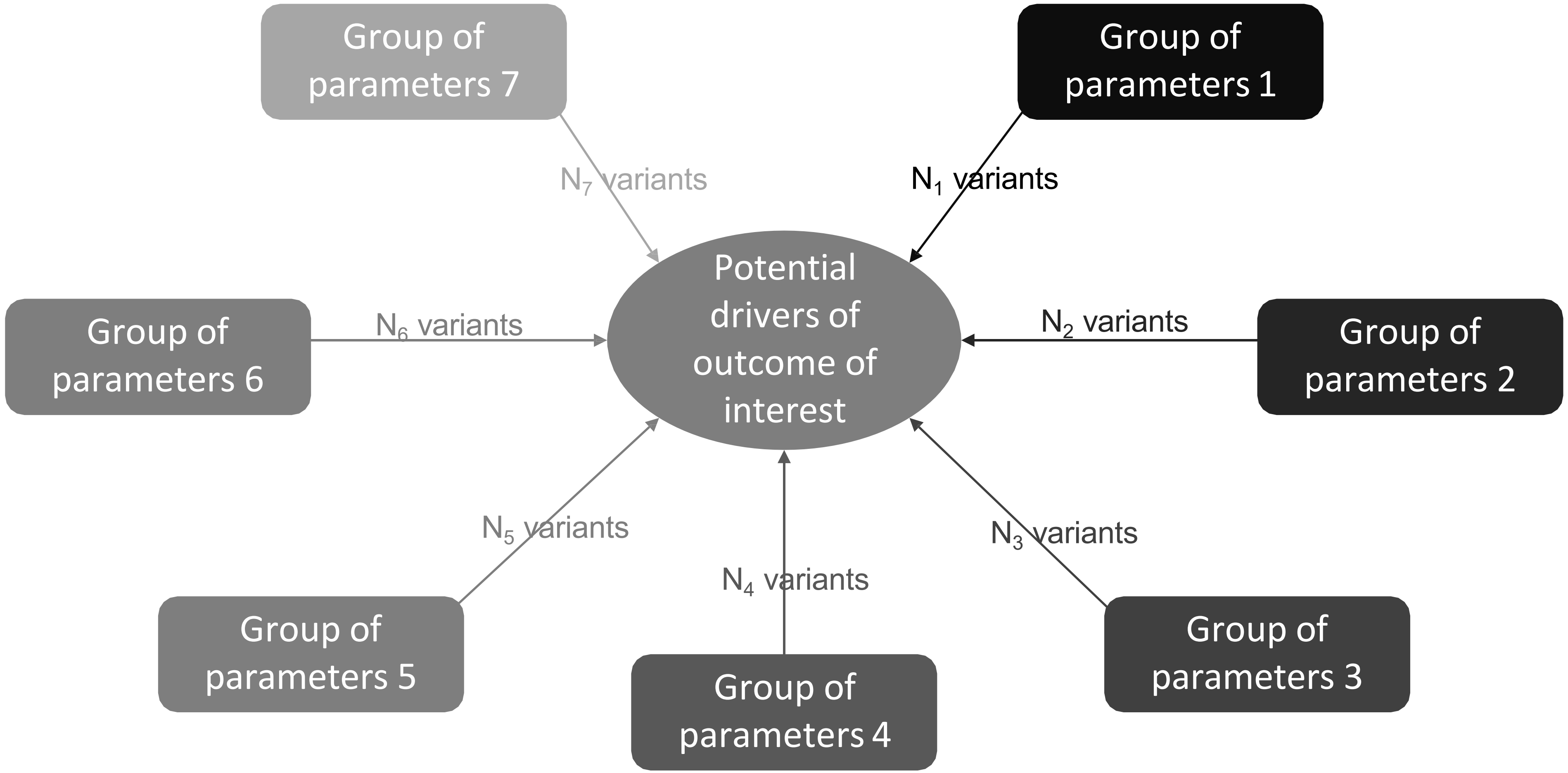
RESEARCH QUESTIONS

- Which uncertain factors have the most influence on the results?
- Which cases (combinations of uncertain factors) lead to specific outcomes?

METHODS

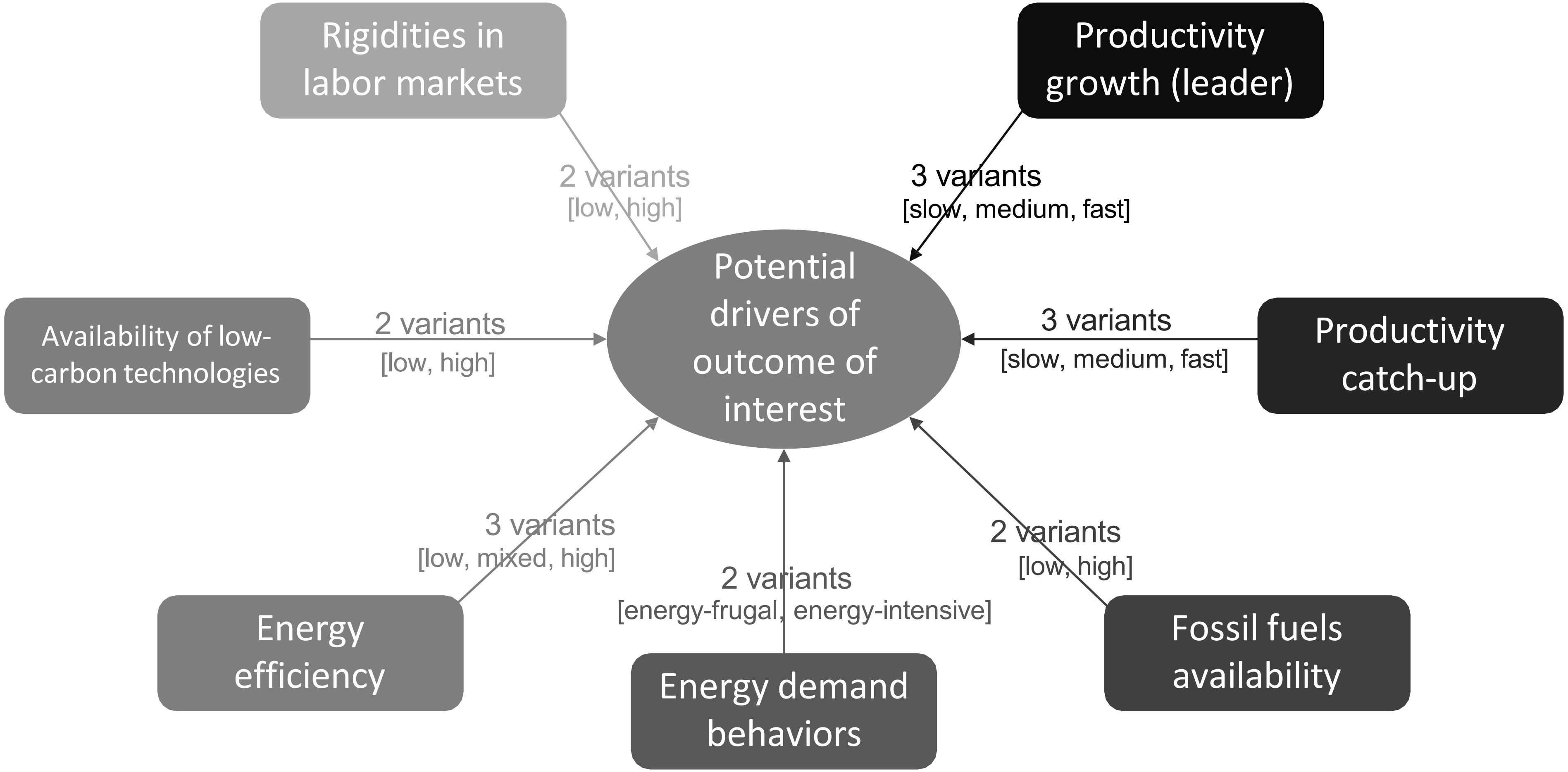
- Constructing (structured) ensembles of scenarios, with the systematic combination of discrete sets of parameters variants (with the Imaclim-R model)
- Analyzing the ensemble to:
  - Highlight which uncertain factors are important [(global) sensitivity analysis]
  - Uncover assumptions that lead scenarios to specific decision-relevant outcomes or vulnerabilities [scenario discovery approach]

Constructing (structured) ensembles of scenarios, with the systematic combination of discrete sets of parameters variants



- $N_1 * N_2 * N_3 * N_4 * N_5 * N_6 * N_7$ model runs (scenarios)

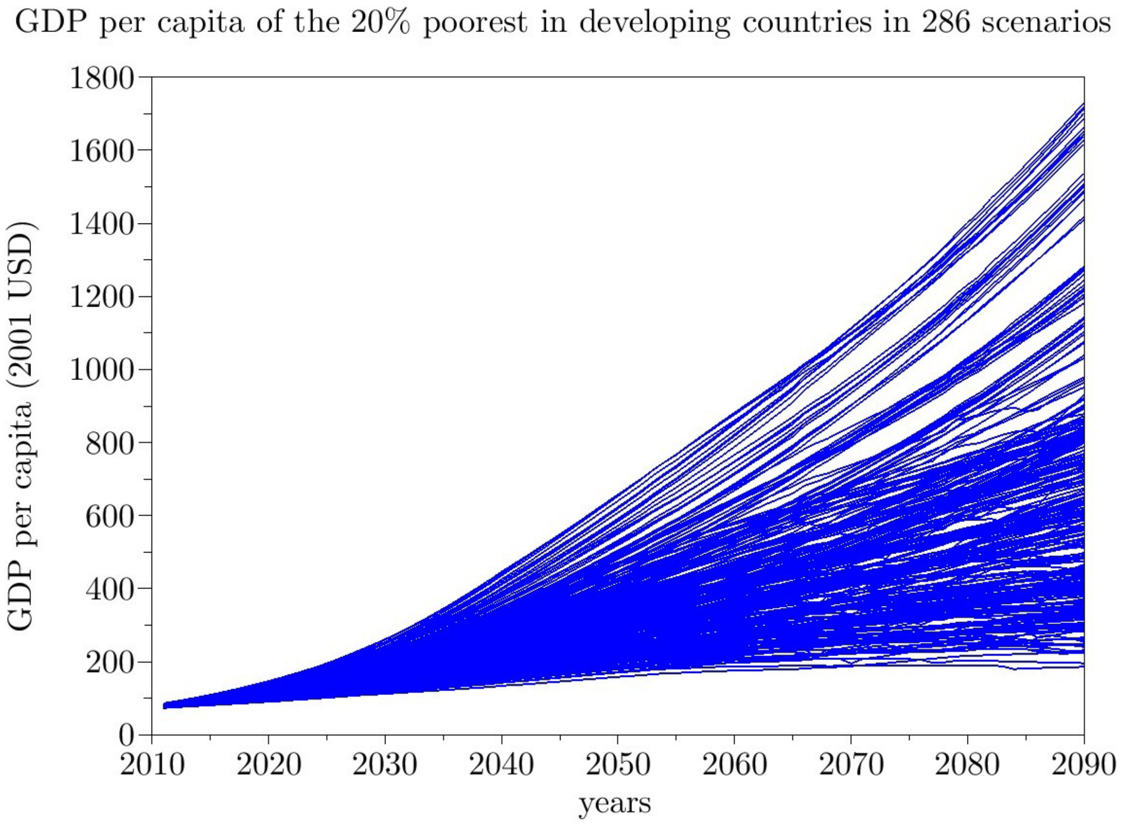
Constructing (structured) ensembles of scenarios, with the systematic combination of discrete sets of parameters variants

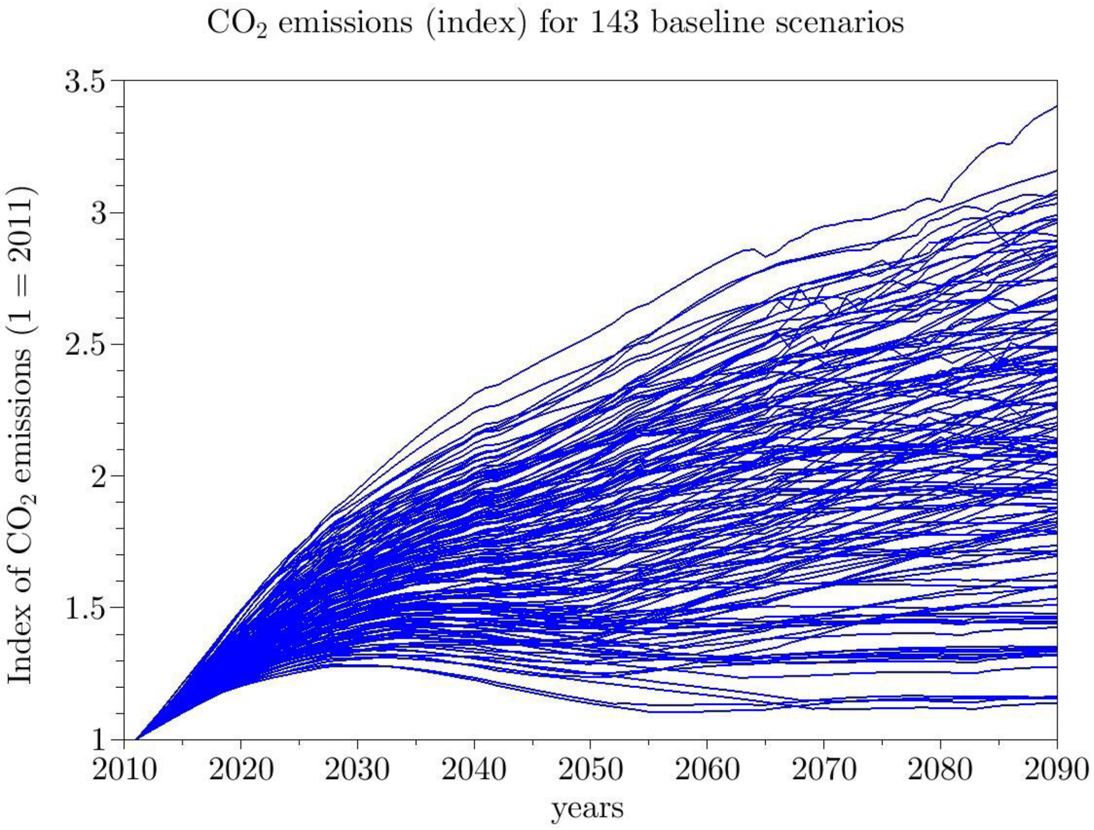


- 432 Imaclim-R model runs ("baseline" scenarios)

Constructing (structured) ensembles of scenarios, with the systematic combination of discrete sets of parameters variants

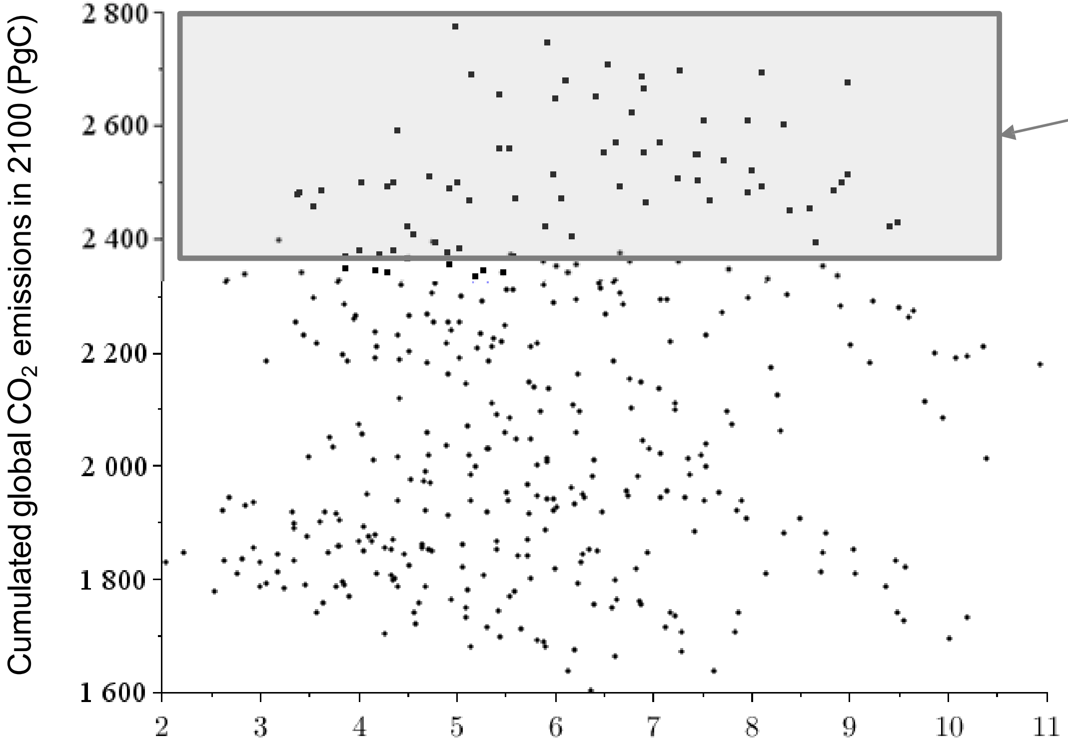
Some illustrative results (extractions from the scenario ensemble)





What combinations of factors may lead to high emissions?

The 432 scenarios plotted according to the global per capita GDP in 2100 (X-axis) and the global cumulated CO_2 emissions in 2100 (Y-axis).



"Scenario discovery" algorithm (PRIM)* to uncover which combinations of input parameters variants lead to high emissions.

* Kwakkel, J. (2017). The Exploratory Modeling Workbench: An open source toolkit for exploratory modeling, scenario discovery, and (multi-objective) robust decision making. Environmental Modelling & Software, 96, 239–250. https://doi.org/10.1016/j.envsoft.2017.06.054 https://github.com/quaquel/EMAworkbench

Guivarch et al. 2016. "The Diversity of Socio-Economic Pathways and CO2 Emissions Scenarios: Insights from the Investigation of a Scenarios Database." doi.org/10.1016/j.envsoft.2016.03.006.

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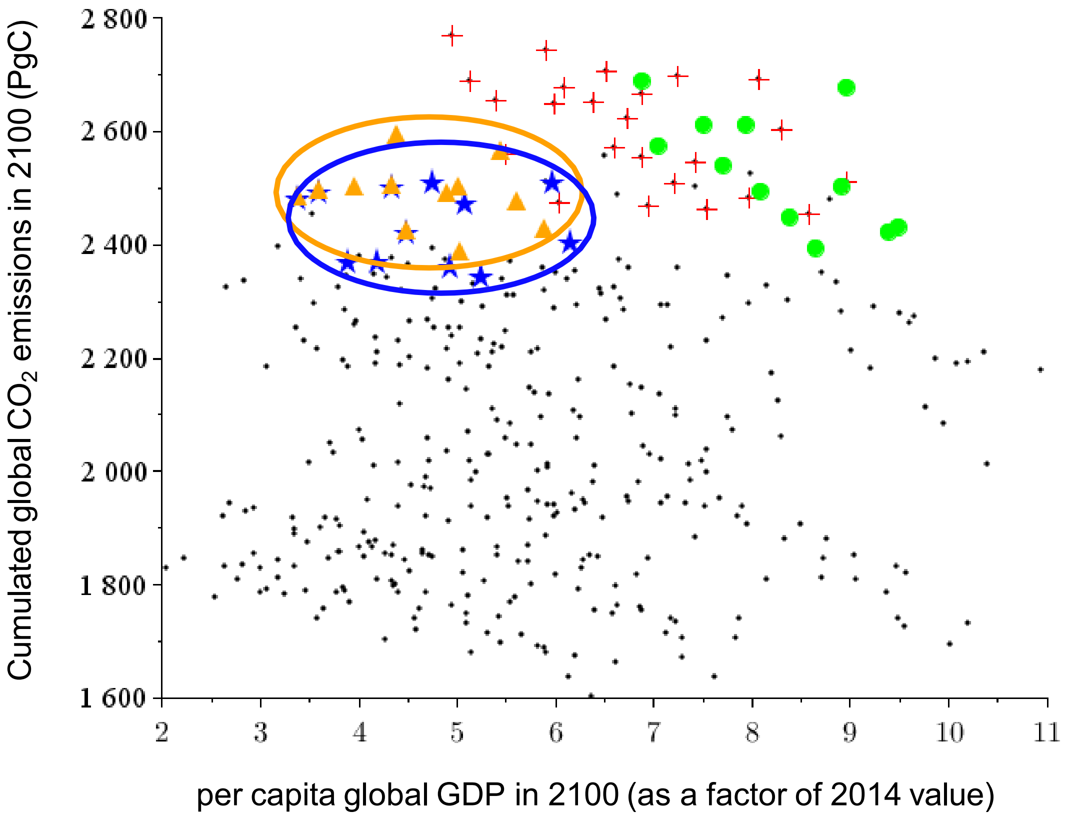


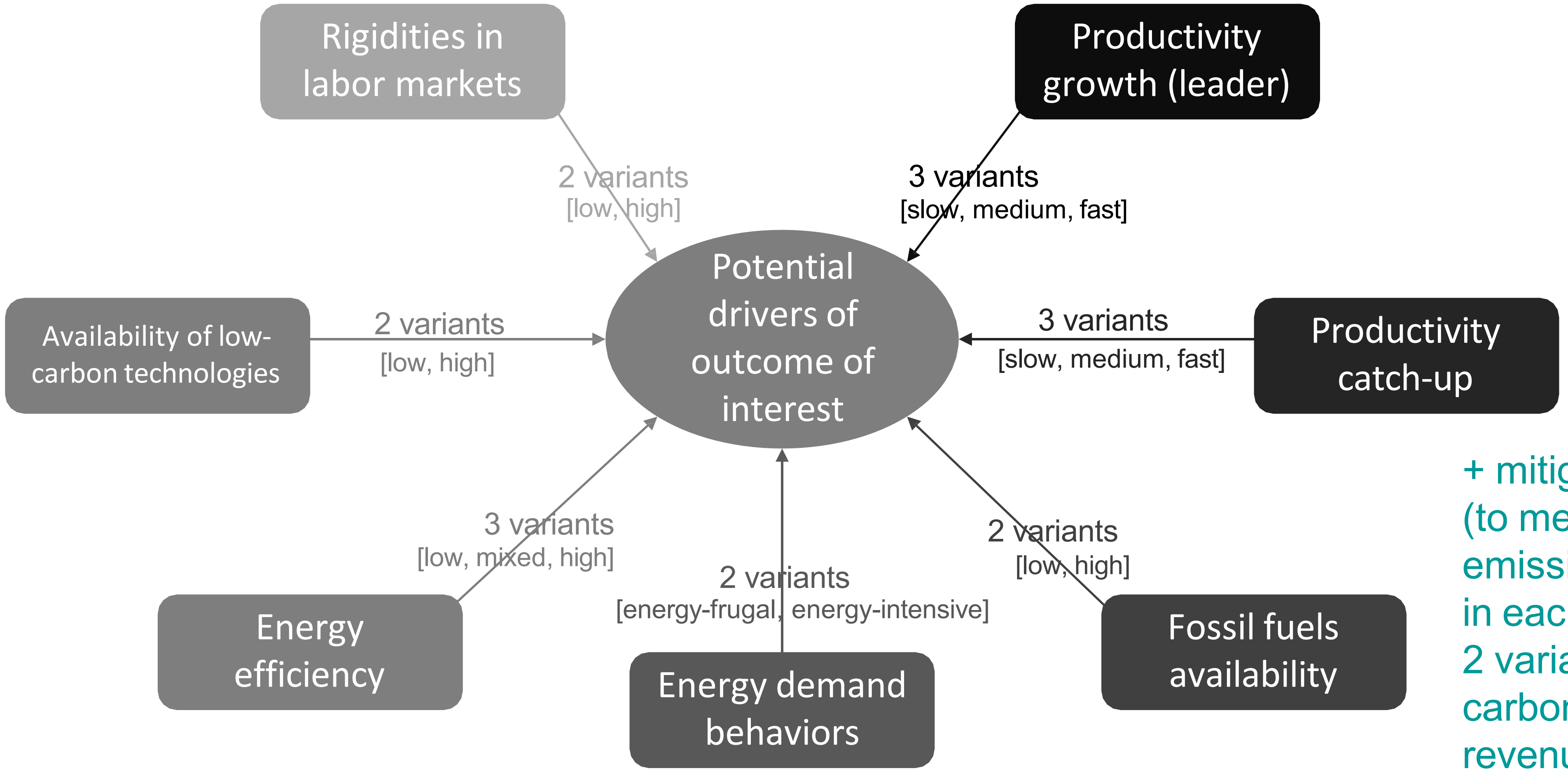
Families of scenarios with high emissions uncovered by the scenario discovery analysis.

		+	★	●	▲
Productivity growth (leader)	slow				
	medium		■		■
	fast	■		■	
Productivity catch-up	slow	■	■		
	medium	■	■		
	fast			■	
Fossil fuels availability	low				
	high	■	■	■	■
Energy demand behaviors	energy-frugal				
	energy-intensive	■	■	■	■
Energy efficiency	low				■
	mixed				
	high				
Availability of low-carbon technologies	low		■		
	high				
Rigidities in labor markets	low				
	high				

■ The grey boxes represent the combinations of parameters values corresponding to each family of scenarios identified.

Guivarch et al. 2016. “The Diversity of Socio-Economic Pathways and CO2 Emissions Scenarios: Insights from the Investigation of a Scenarios Database.” doi.org/10.1016/j.envsoft.2016.03.006.

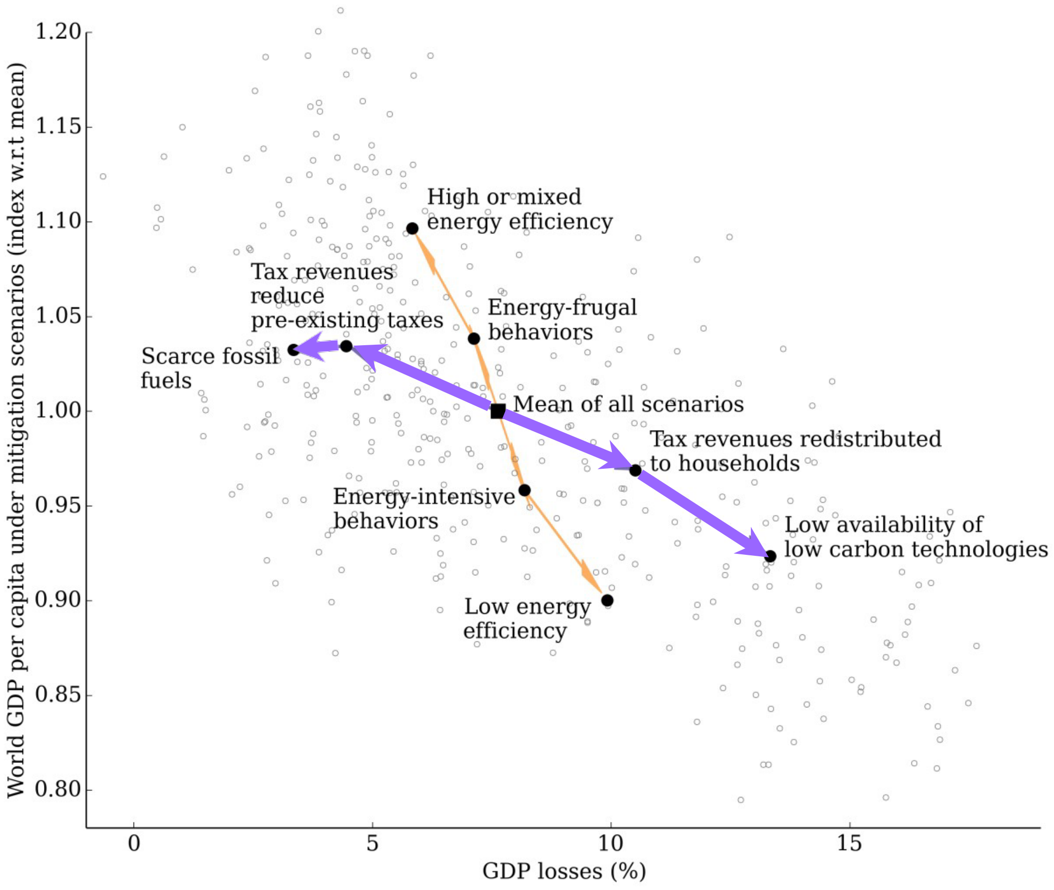
Constructing (structured) ensembles of scenarios, with the systematic combination of discrete sets of parameters variants



+ mitigation policies (to meet a given emission pathway) in each “case”, with 2 variants for carbon tax revenues use

- 432 Imaclim-R model runs (“baseline” scenarios)
- 864 mitigation scenarios

? Which factors most influence mitigation costs, and growth in mitigation scenarios?

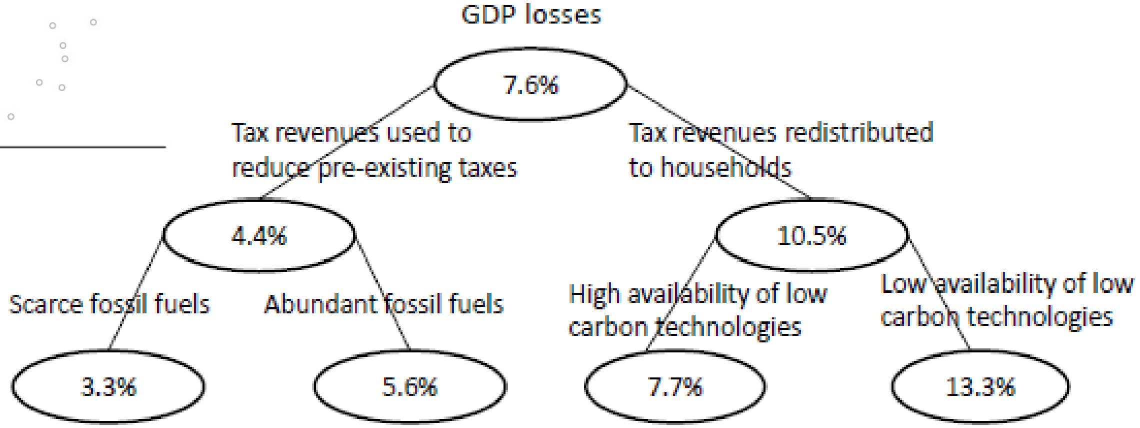


- mitigation scenarios.
- average across the subset of scenarios that share common assumptions explained by the adjacent caption.

The first two discriminating drivers for:

- (purple arrow) the GDP losses
- (orange arrow) the global per capita GDP in the mitigation scenarios.

Classification and Regression Tree (CART)*



* Kwakkel, J. (2017). The Exploratory Modeling Workbench: An open source toolkit for exploratory modeling, scenario discovery, and (multi-objective) robust decision making. Environmental Modelling & Software, 96, 239–250. https://doi.org/10.1016/j.envsoft.2017.06.054
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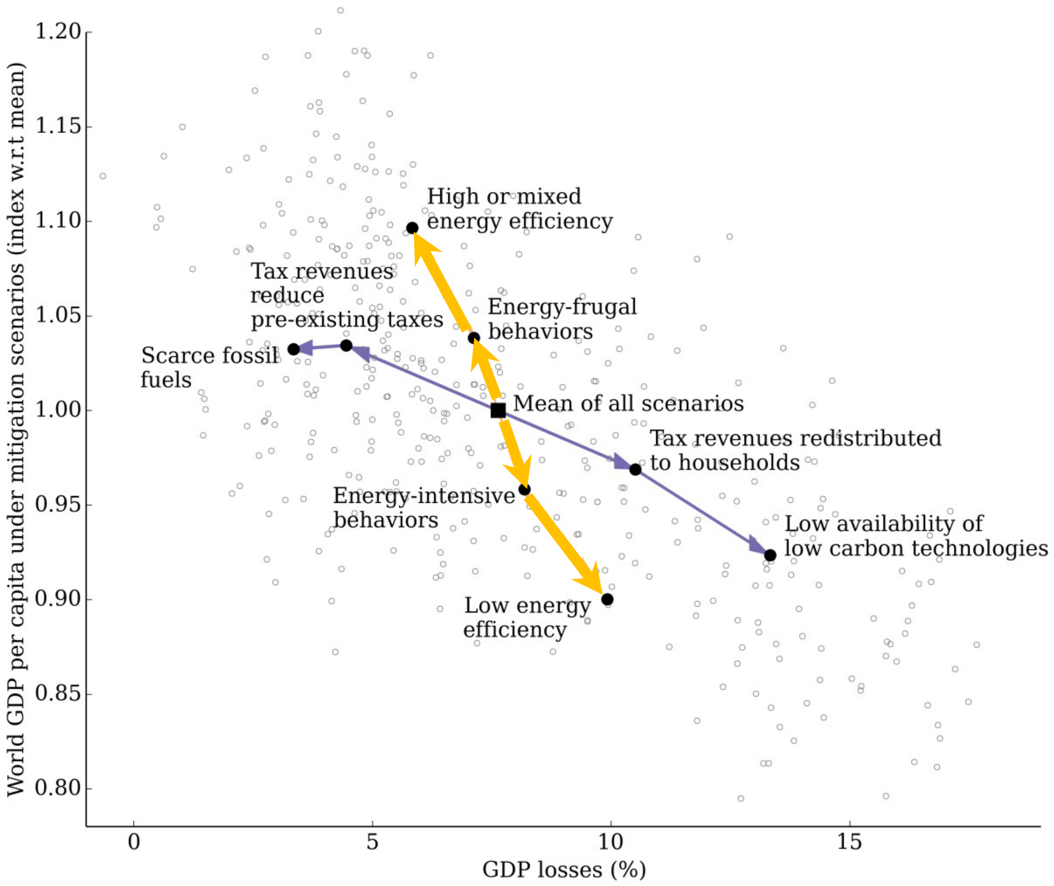

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The first two discriminating drivers for:

- → the GDP losses
- → the global per capita GDP in the mitigation scenarios.

Rozenberg, Julie and Céline Guivarch. “GDP losses and GDP levels associated with mitigation pathways: main sources of uncertainty”. Not (yet) published.

Picture by Jakub Kriz on Unsplash

Exploring uncertainty in model forms

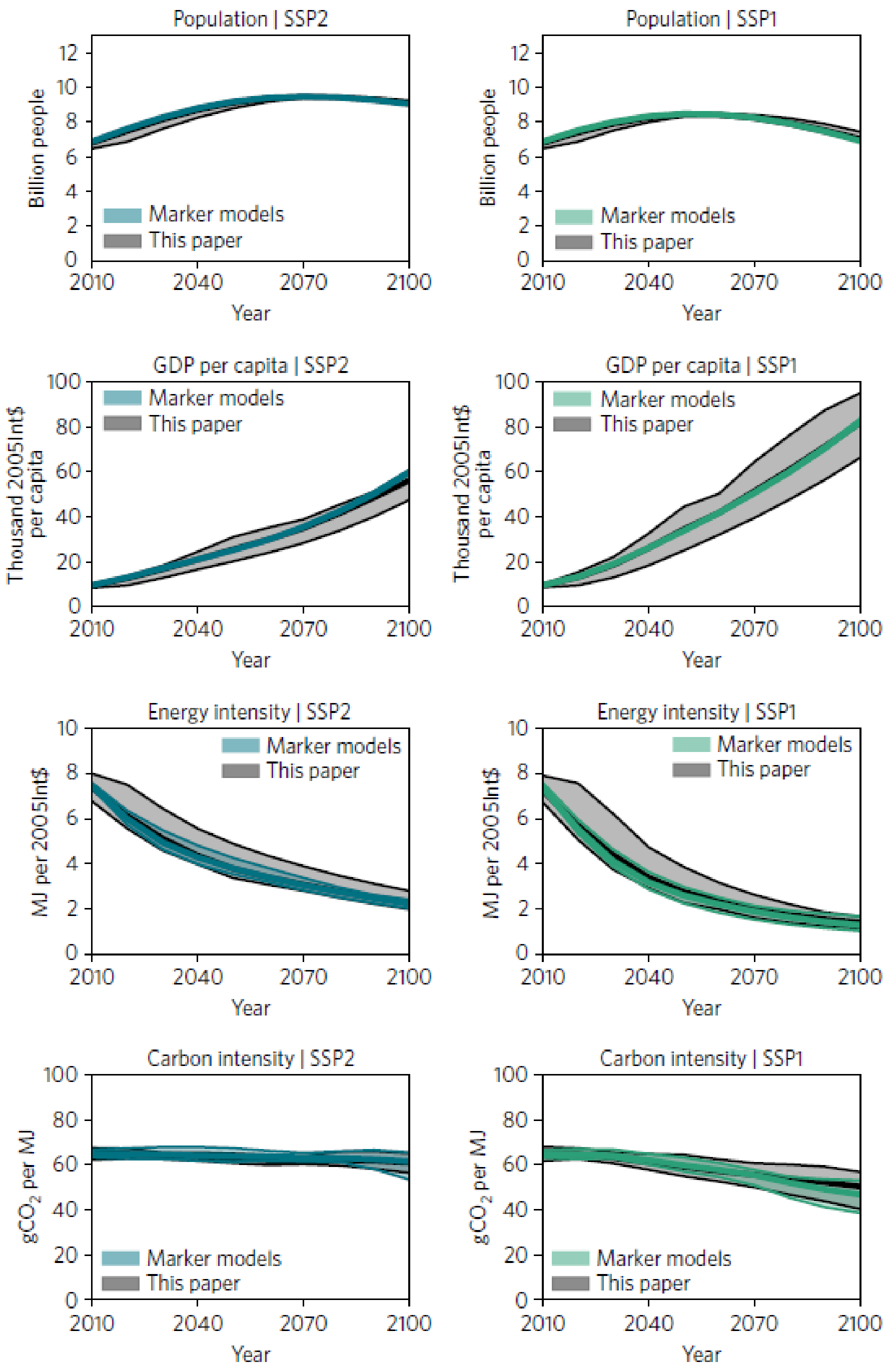
Two examples with several IAMs and a few or many scenarios

Marangoni, G., M. Tavoni, V. Bosetti, E. Borgonovo, P. Capros, O. Fricko, D. E. H. J. Gernaat, et al. 2017. “Sensitivity of Projected Long-Term CO2 Emissions across the Shared Socioeconomic Pathways.” Nature Climate Change. https://doi.org/10.1038/nclimate3199.

Taconet, Nicolas, Aurélie Méjean, and Céline Guivarch. 2020. “Influence of Climate Change Impacts and Mitigation Costs on Inequality between Countries.” Climatic Change 160 (1): 15–34. https://doi.org/10.1007/s10584-019-02637-w.

What are the key drivers of future CO_2 emissions?

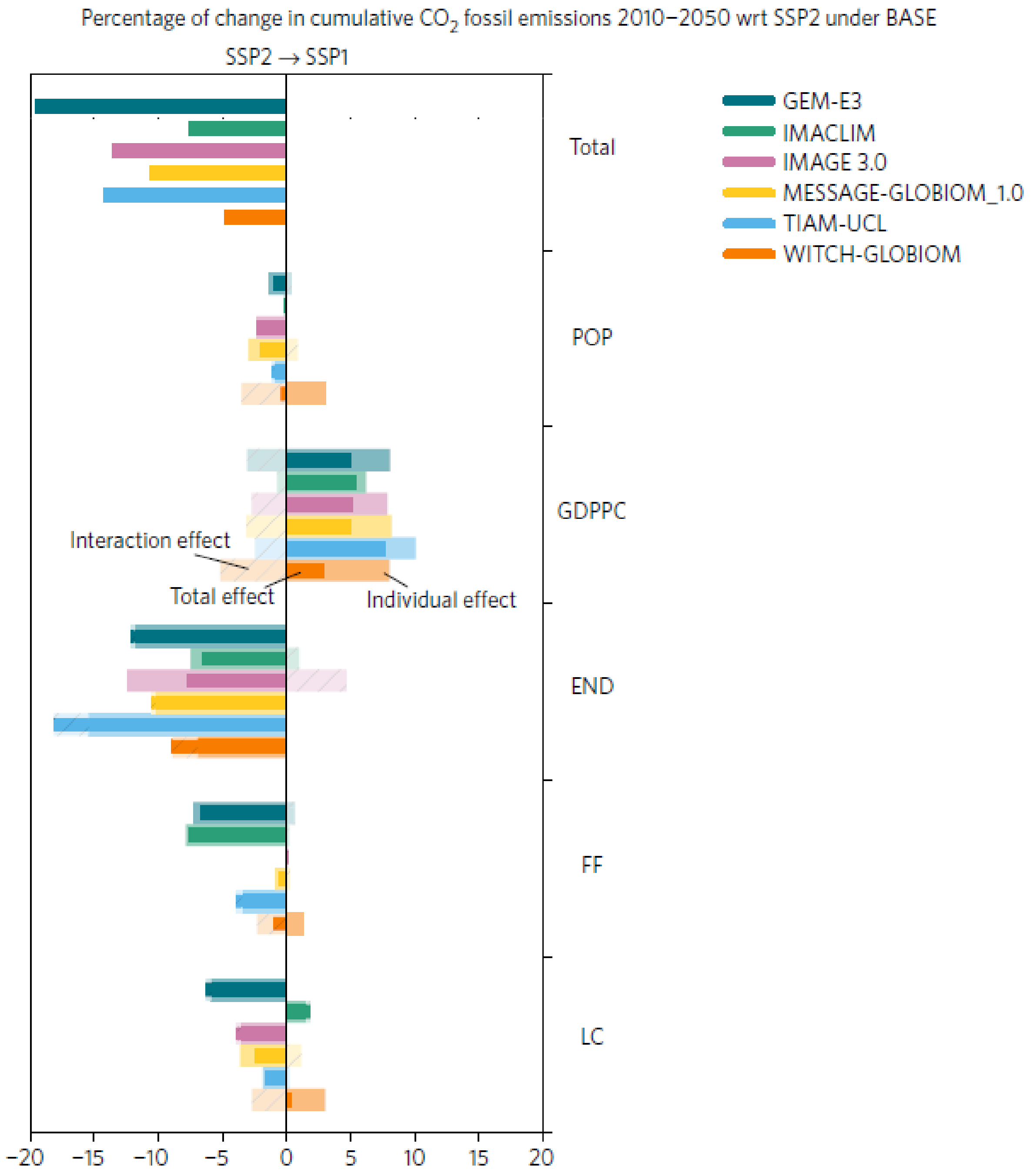
- Study the impact of five families of parameters, related to population, income, energy efficiency, fossil fuel availability, and low-carbon energy technology development
- 6 IAMs with different structural characteristics
- A sensitivity analysis algorithm that allows to parsimoniously compute both the direct and interaction effects of each of these drivers on cumulative emissions



Marangoni et al. 2017. “Sensitivity of Projected Long-Term CO2 Emissions across the Shared Socioeconomic Pathways.” Nature Climate Change. https://doi.org/10.1038/nclimate3199.

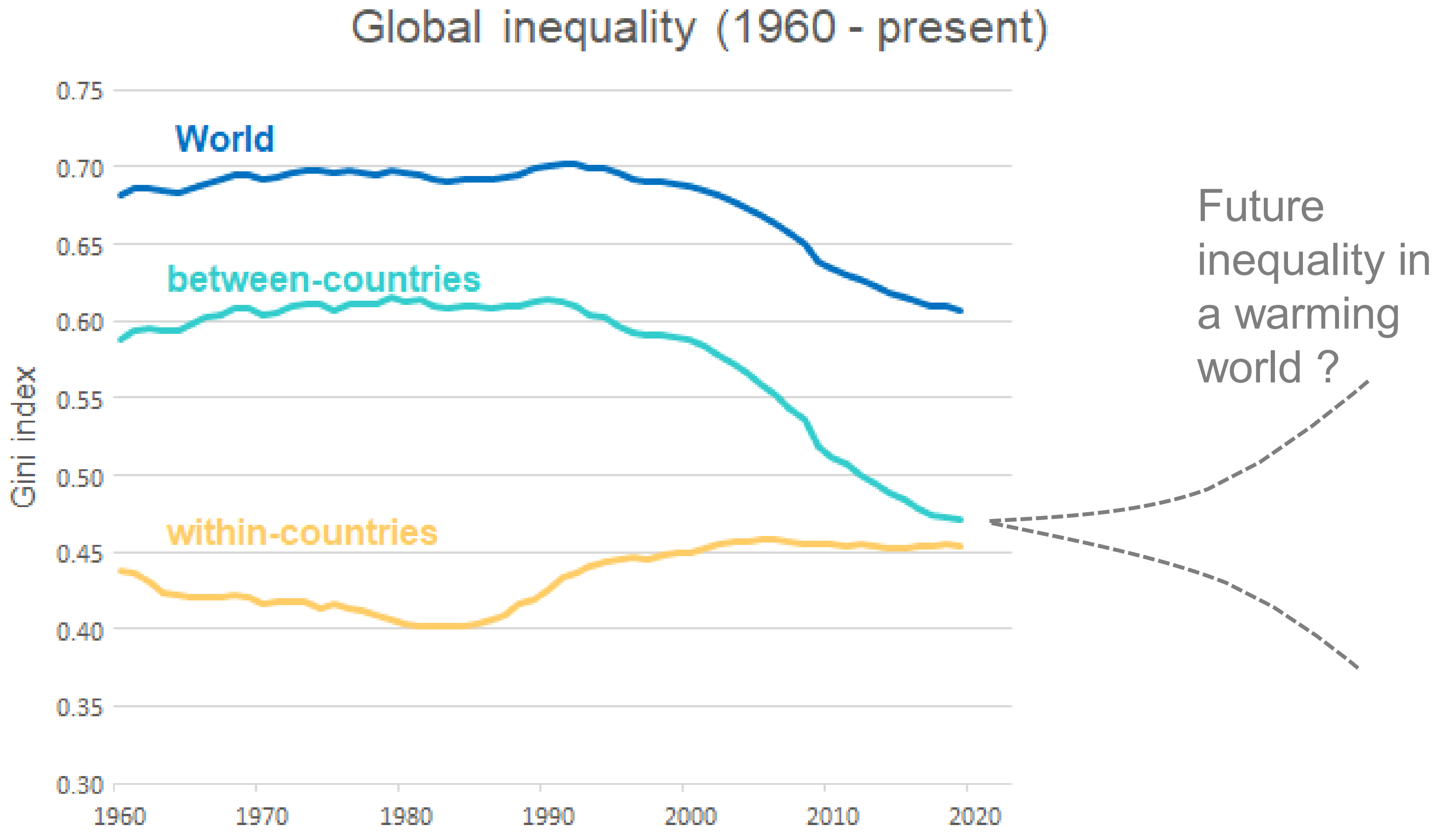
? What are the key drivers of future CO_2 emissions?

- The SSP assumptions about energy intensity and economic growth are the most important determinants of future CO_2 emissions from energy combustion.
- Interaction terms between parameters are important determinants of the total sensitivities.



Marangoni et al. 2017. "Sensitivity of Projected Long-Term CO2 Emissions across the Shared Socioeconomic Pathways." Nature Climate Change. https://doi.org/10.1038/nclimate3199.

What are the prospects for future inequality between countries under climate change?



Data from https://www.wider.unu.edu/database/world-income-inequality-database-wiid

Taconet et al. 2020. "Influence of Climate Change Impacts and Mitigation Costs on Inequality between Countries." Climatic Change 160 (1): 15–34. https://doi.org/10.1007/s10584-019-02637-w.

? What are the prospects for future inequality between countries under climate change?

- How much convergence between countries will continue and how fast (demographic, socio-economic, education, institutions, technical progress assumptions)?
- How large will the impacts of climate change be, and how unevenly distributed between countries?
- How large will the costs of climate change mitigation be, and how unevenly distributed across countries?

Taconet et al. 2020. “Influence of Climate Change Impacts and Mitigation Costs on Inequality between Countries.” Climatic Change 160 (1): 15–34. https://doi.org/10.1007/s10584-019-02637-w.

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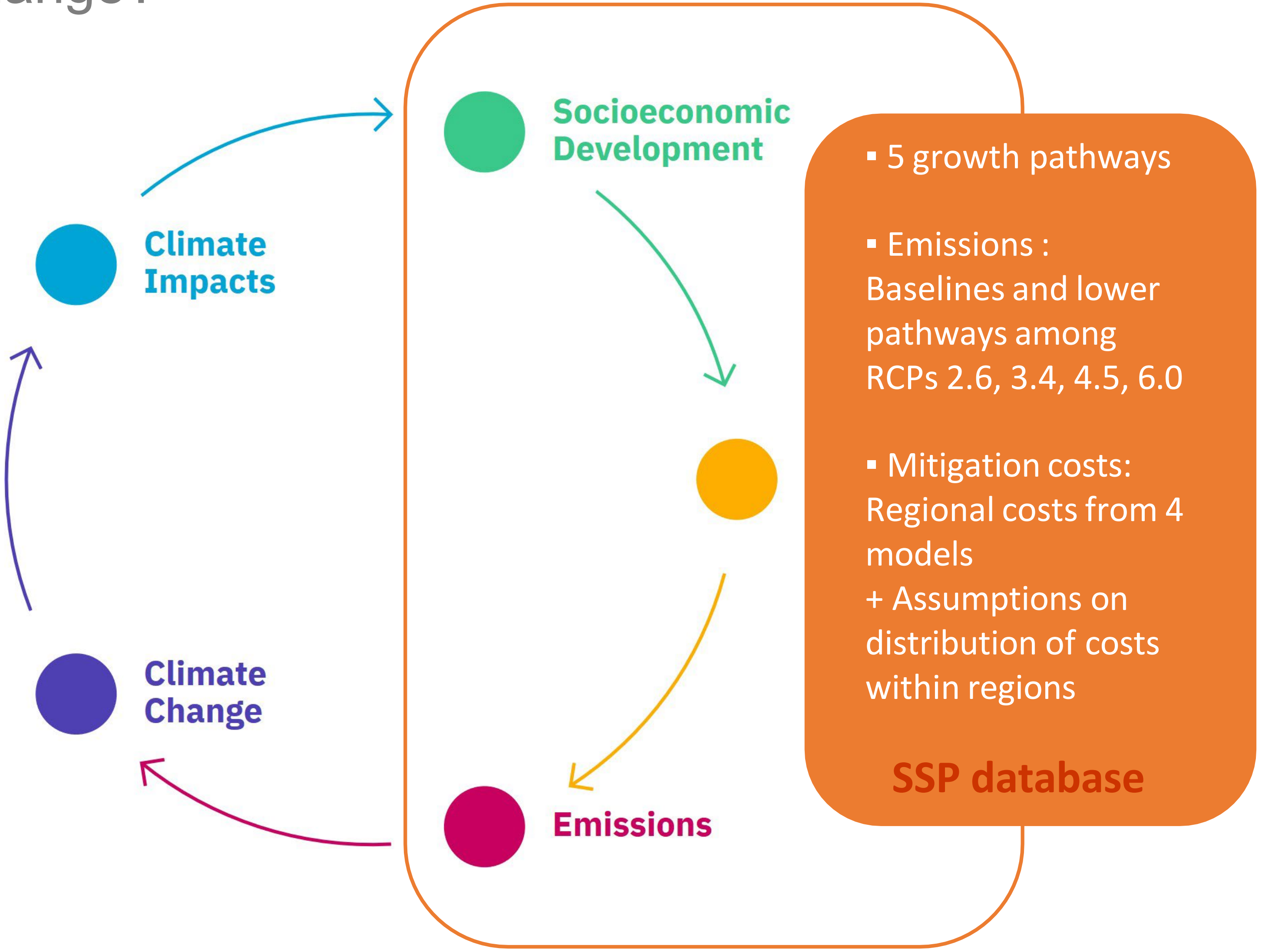

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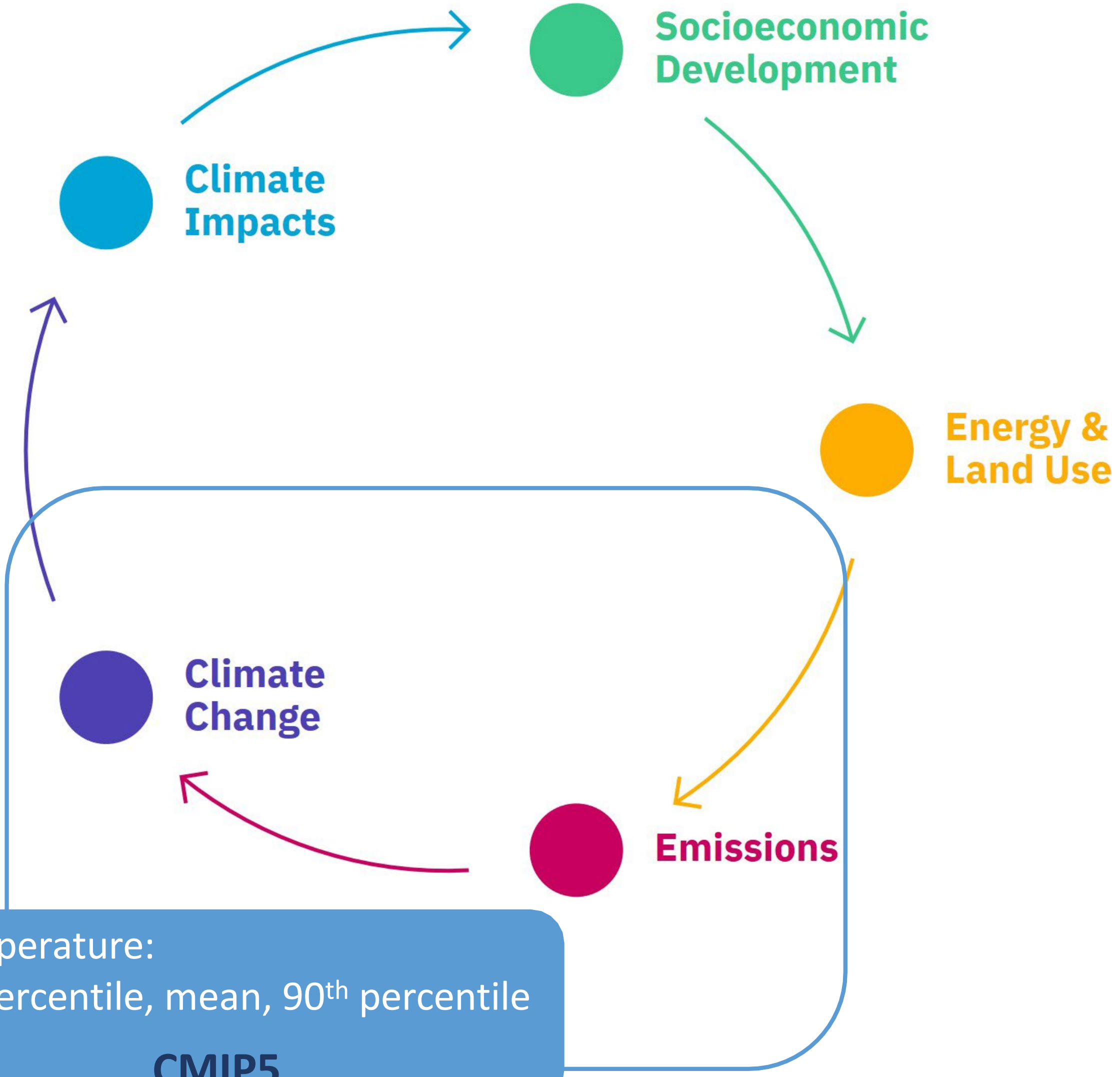


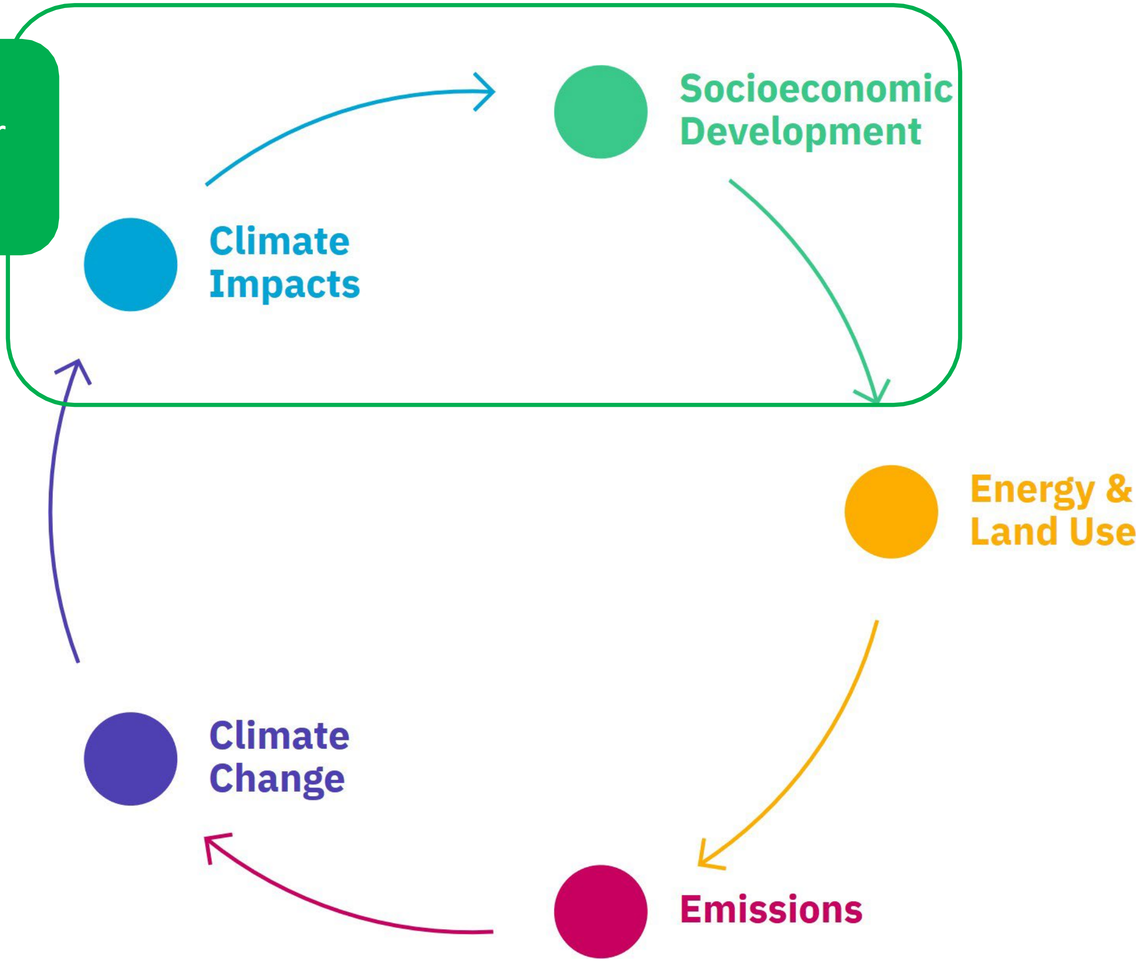
- Temperature:
  10^{th} percentile, mean, 90^{th} percentile

CMIP5

Taconet et al. 2020. "Influence of Climate Change Impacts and Mitigation Costs on Inequality between Countries." Climatic Change 160 (1): 15–34. https://doi.org/10.1007/s10584-019-02637-w.

What are the prospects for future inequality between countries under climate change?

- Economic impacts :
8 damage functions (IAM- or econometrics-based*)



* from RICE2010, Roson and Sartori (2016), Dell et al. (2012); Burke et al. (2015)

? What are the prospects for future inequality between countries under climate change?

- ➢ 3408 scenarios, projections of GDP and GDP per capita for 161 countries, up to 2100.

- ➢ Gini coefficient of inequality between countries (population-weighted international inequality).

? What are the prospects for future inequality between countries under climate change?

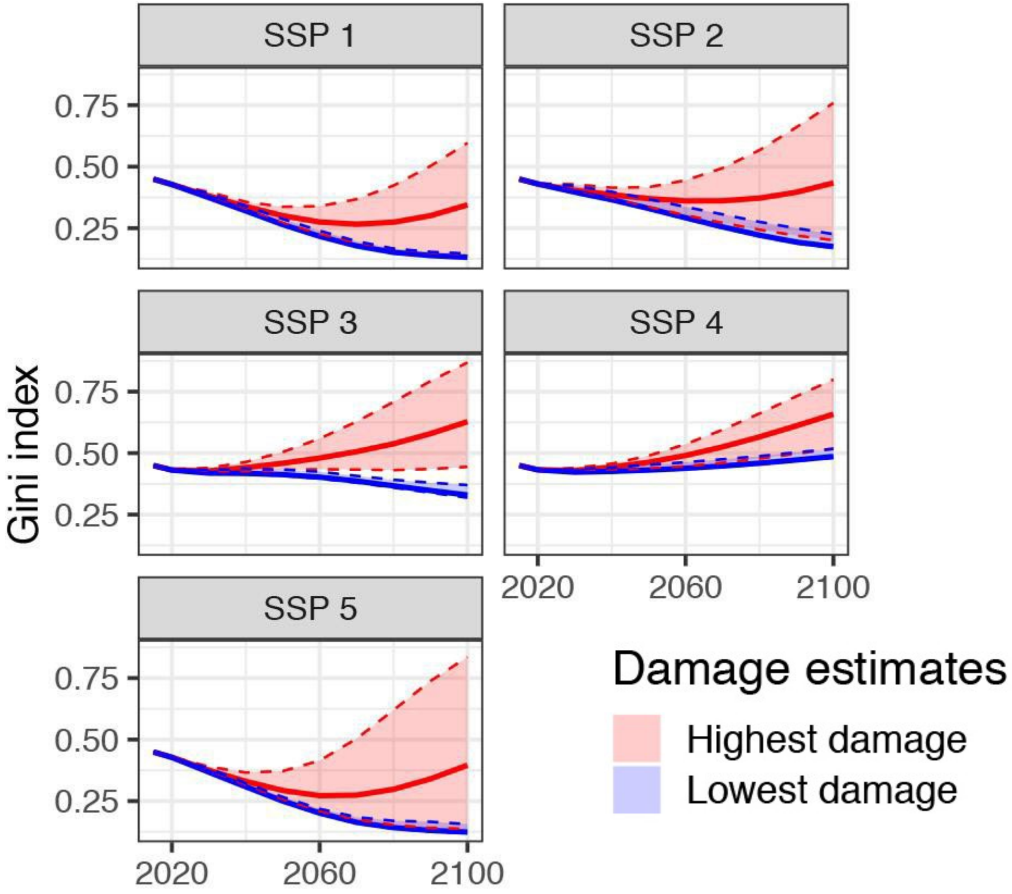


Figure from www.carbonbrief.org/guest-post-climate-change-could-reverse-falling-inequality-between-countries

Evolution of the Gini index in the 21st century for different socioeconomic pathways, numbered SSP1-5, and under different estimates of climate change damages

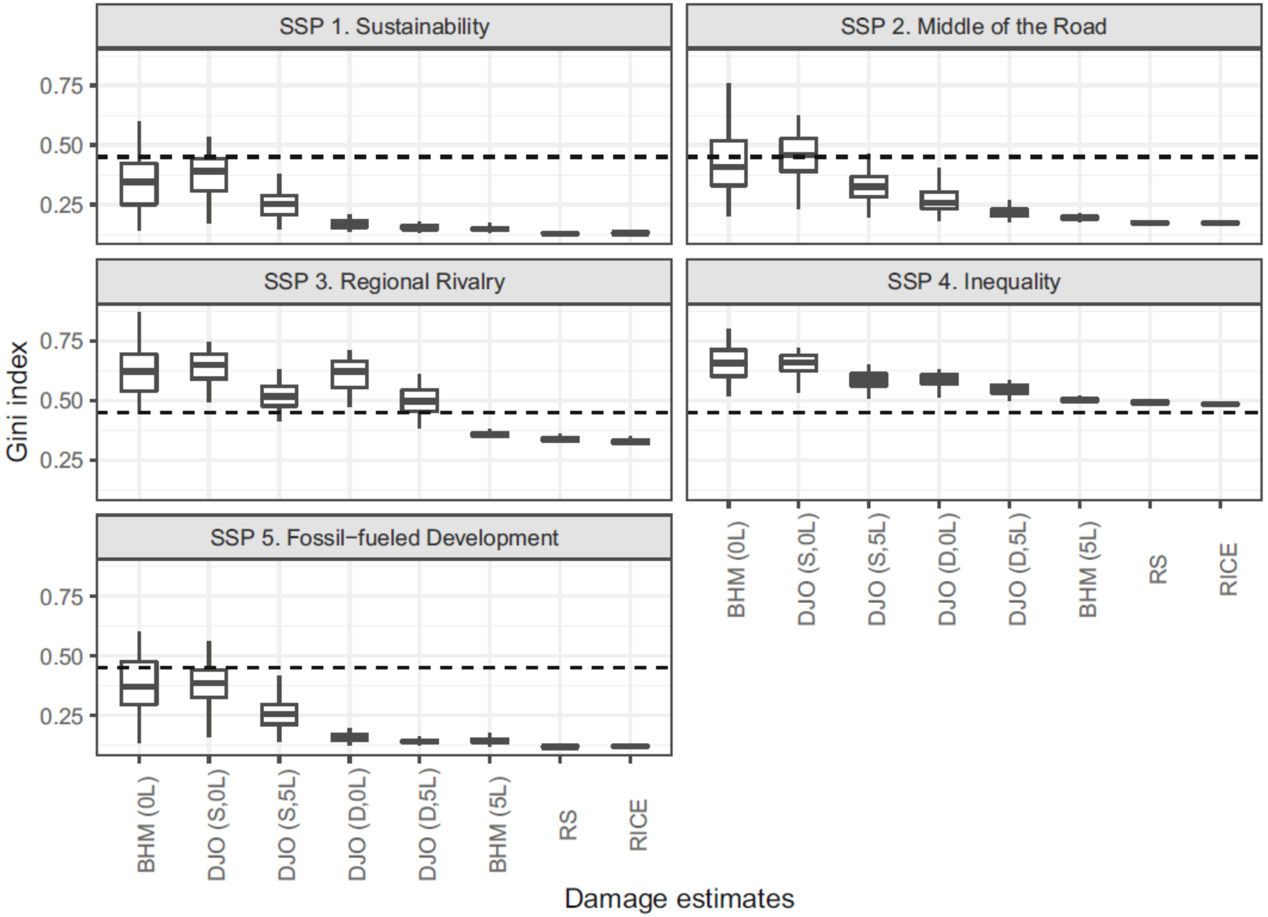
What are the prospects for future inequality between countries under climate change?

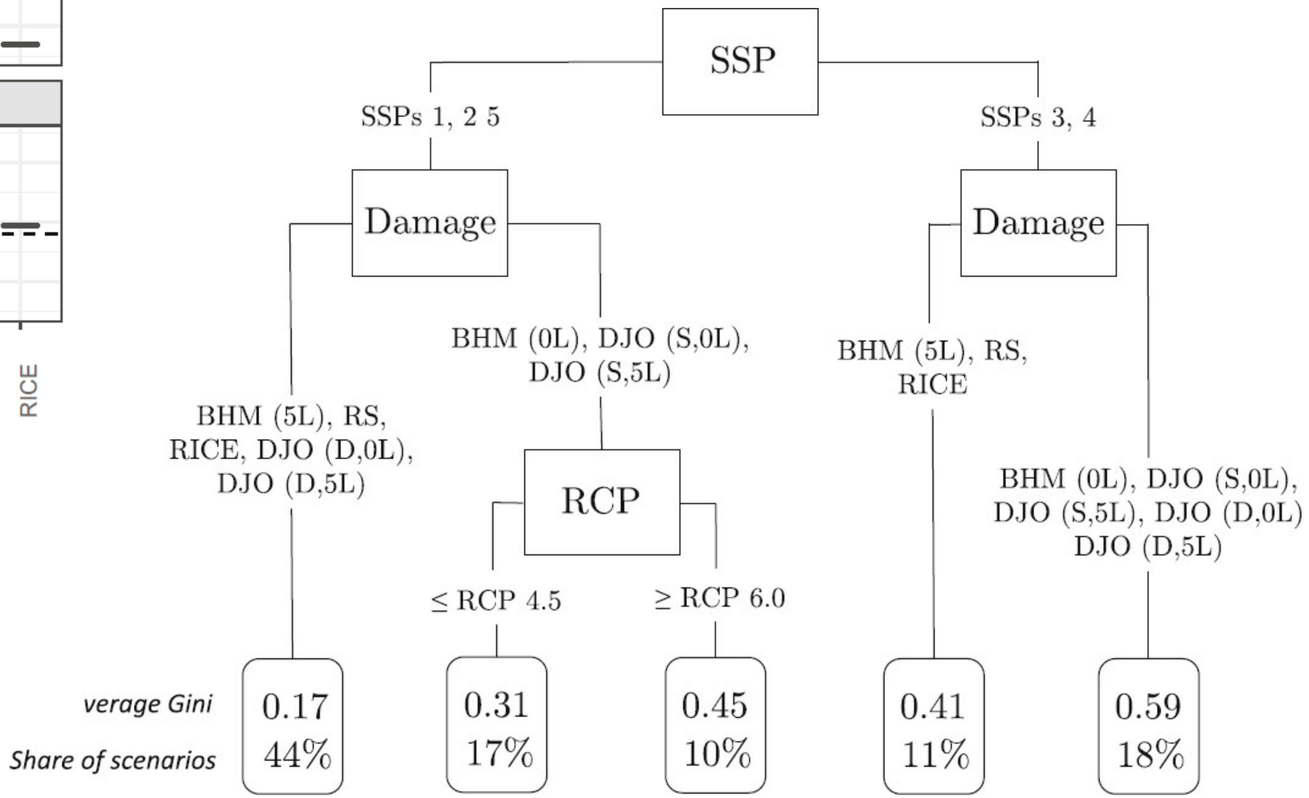
Table of the combinations of factors leading to a trend reversal in inequalities over time

SSP	Damage	RCP	Temperature response
	BHM (0L)	≥ RCP 3.4	All
SSP 1	DJO (S,5L)	All	Medium, High
	DJO (S,0L)	≥ RCP 3.4	All
	BHM (0L)	≥ RCP 3.4	Medium, High
SSP2	DJO (S,5L)	≥ RCP 3.4	Medium, High
	DJO (S,0L)	≥ RCP 3.4	All
	BHM (0L)		
	DJO (S,5L)		
SSP3	DJO (S,0L)	All	All
	DJO (D,0L)		
	DJO (D,5L)		
SSP4	All	All	All
	BHM (0L)	≥ RCP 3.4	
SSP5	DJO (S,5L)	≥ RCP 3.4	All
	DJO (S,0L)	≥ RCP 3.4	

Taconet et al. 2020. “Influence of Climate Change Impacts and Mitigation Costs on Inequality between Countries.” Climatic Change 160 (1): 15–34. https://doi.org/10.1007/s10584-019-02637-w.

? What are the prospects for future inequality between countries under climate change?



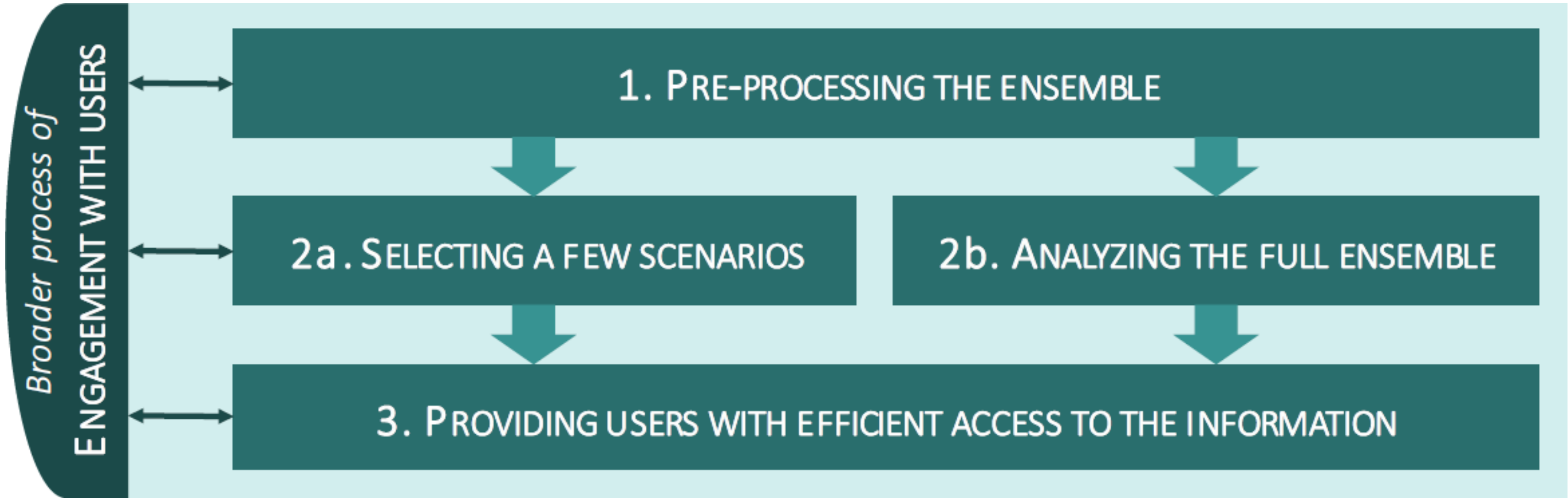


Taconet et al. 2020. "Influence of Climate Change Impacts and Mitigation Costs on Inequality between Countries." Climatic Change 160 (1): 15–34. https://doi.org/10.1007/s10584-019-02637-w.

Using large ensembles of climate change mitigation scenarios for robust insights

More examples, as well as a perspective on key methodological issues, existing methods and applications to address them, as well as future developments that are still needed in:

Guivarch, Céline, Thomas Le Gallic, Nico Bauer, Panagiotis Fragkos, Daniel Huppmann, Marc Jaxa-Rozen, Ilkka Keppo, et al. 2022. “Using Large Ensembles of Climate Change Mitigation Scenarios for Robust Insights.” Nature Climate Change 12 (5): 428–35. https://doi.org/10.1038/s41558-022-01349-x.



Picture by Jakub Kriz on Unsplash

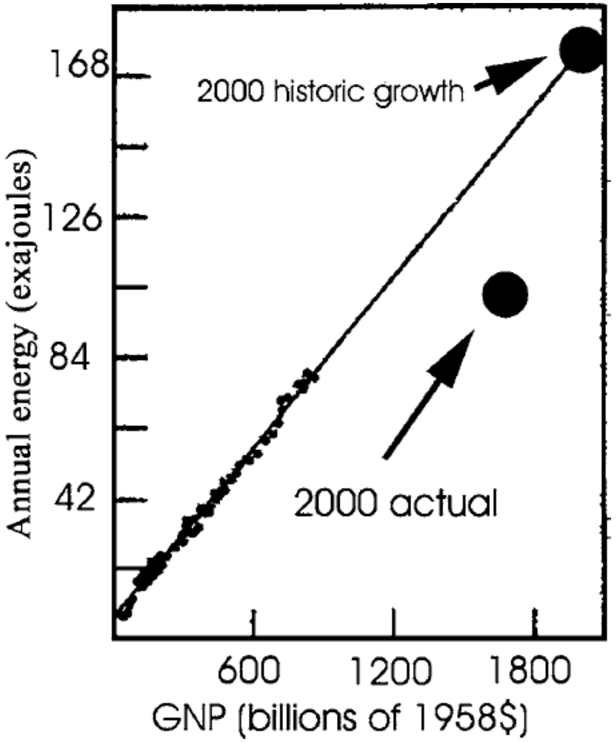
1. Some frameworks to think about uncertainty and modelling

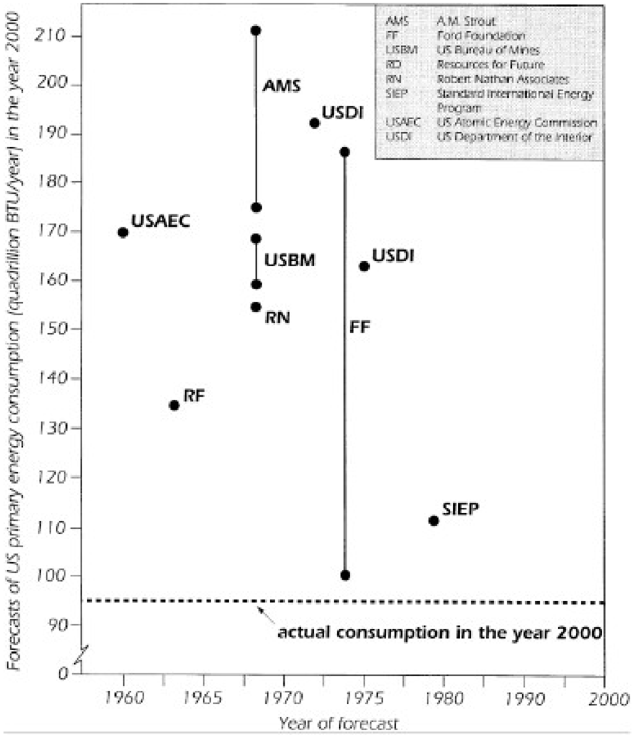
2. Some case studies

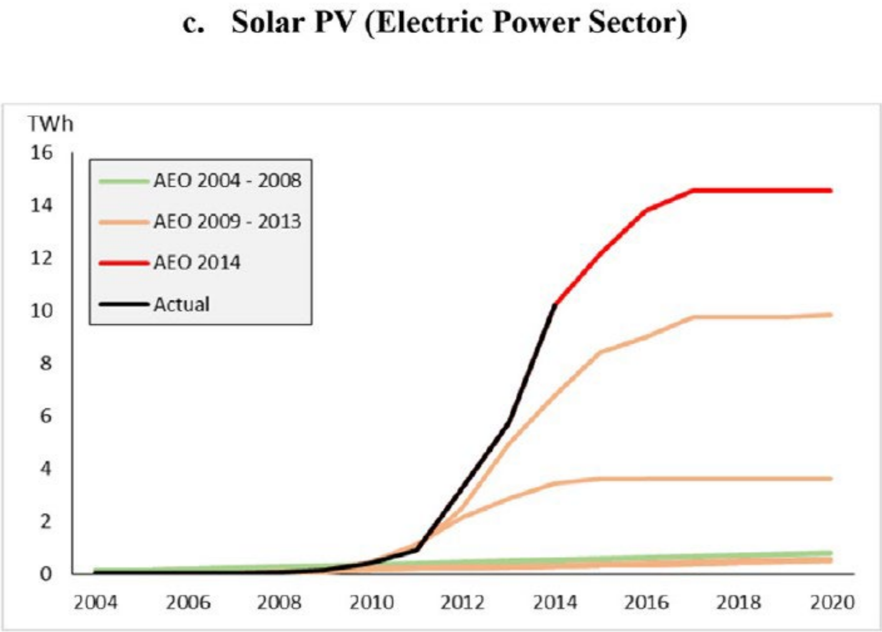
3. Some conclusive remarks

Humility

- “Models”/”scenarios”/”you”/”we” will be wrong.







Craig et al. 2002. "What Can History Teach Us? A Retrospective Examination of Long-Term Energy Forecasts for the United States." *Annual Review of Energy and the Environment* 27 (1): 83–118. https://doi.org/10.1146/annurev.energy.27.122001.083425.

Smil, Vaclav. 2000. "Perils of Long-Range Energy Forecasting: Reflections on Looking Far Ahead." *Technological Forecasting and Social Change* 65 (3): 251–64. https://doi.org/10.1016/S0040-1625(99)00097-9

Gilbert, Alexander Q., and Benjamin K. Sovacool. 2016. "Looking the Wrong Way: Bias, Renewable Electricity, and Energy Modelling in the United States." *Energy* 94 (January): 533–41. https://doi.org/10.1016/j.energy.2015.10.135.

Humility

- “Models”/”scenarios”/”you”/”we” will be wrong.

- Although scenarios are designed to explore the possibility space, even large scenario ensembles do not fully or equally explore the space of possibilities.

Responsibility

- Model results can inform/influence choices and decisions [performativity]
  - Modeling decisions may narrow or broaden the content of policy deliberation
  - Studying certain scenarios/mitigation options, technologies or policies may very well make them more (or less?) probable/desirable/feasible
- Ponder the tension between excluding scenarios that are judged "inappropriate" and missing some low-probability high-risk type of scenario or those that represent future discontinuities.

- Communicating uncertainty is tricky
- Highlight results robust to uncertainties covered, or illuminate the key factors influencing the results
- Between Scylla and Charybdis:
  - False precision and overconfidence,
  - False impression of ignorance deterring action (+ misunderstanding, manipulated or fabricated uncertainty)
- Adapt to the audience, test and evaluate communication/visualization tools and choices

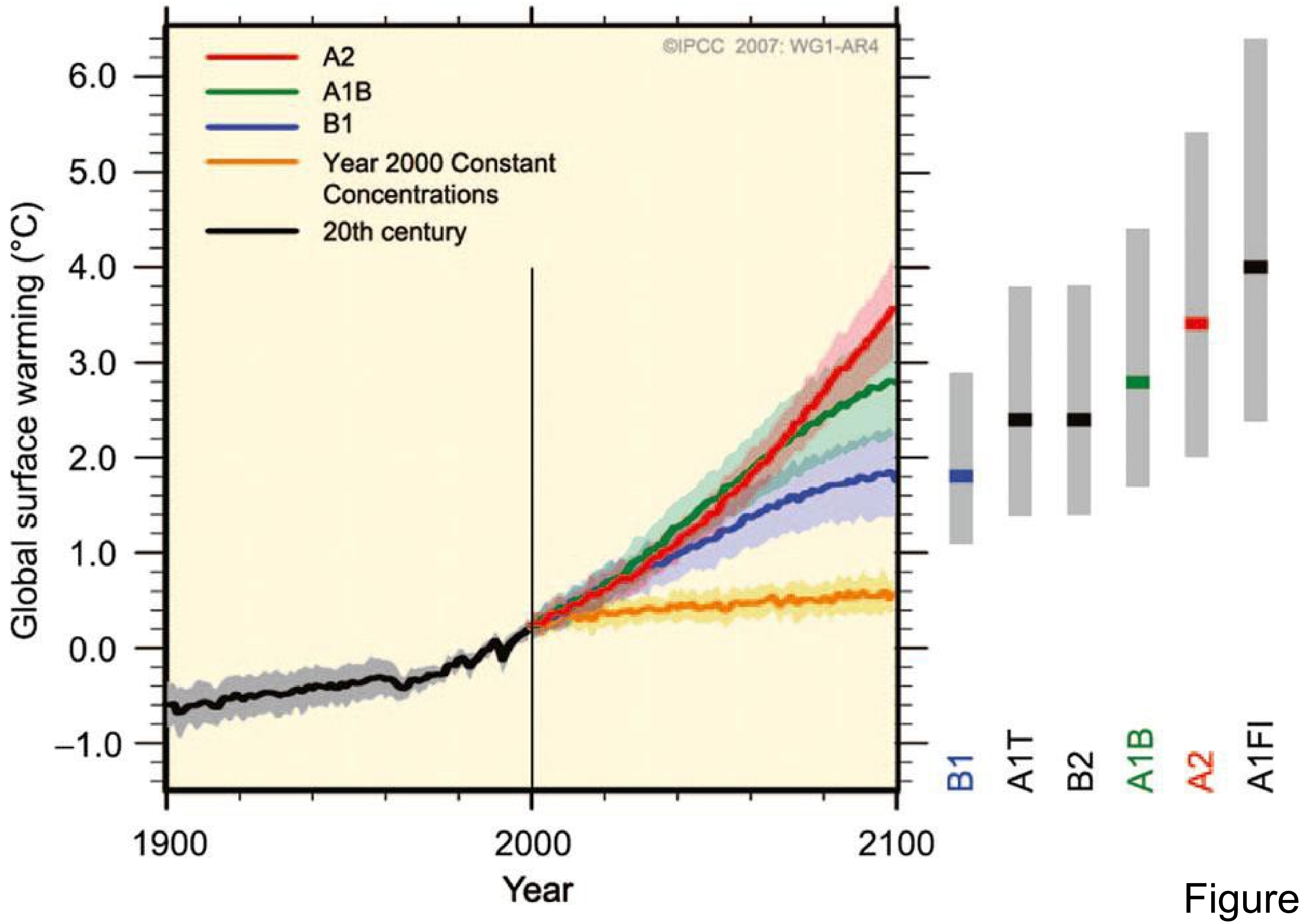
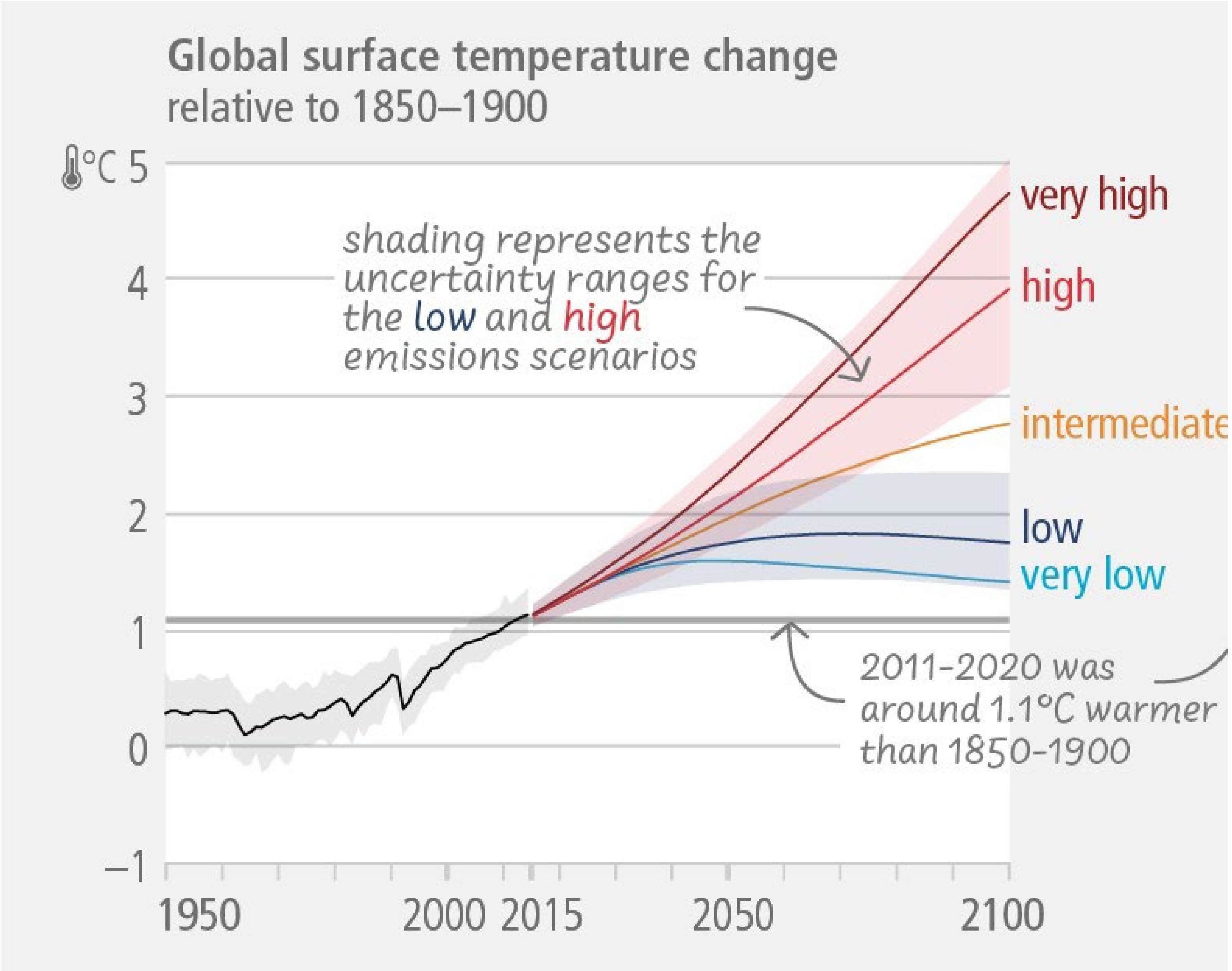
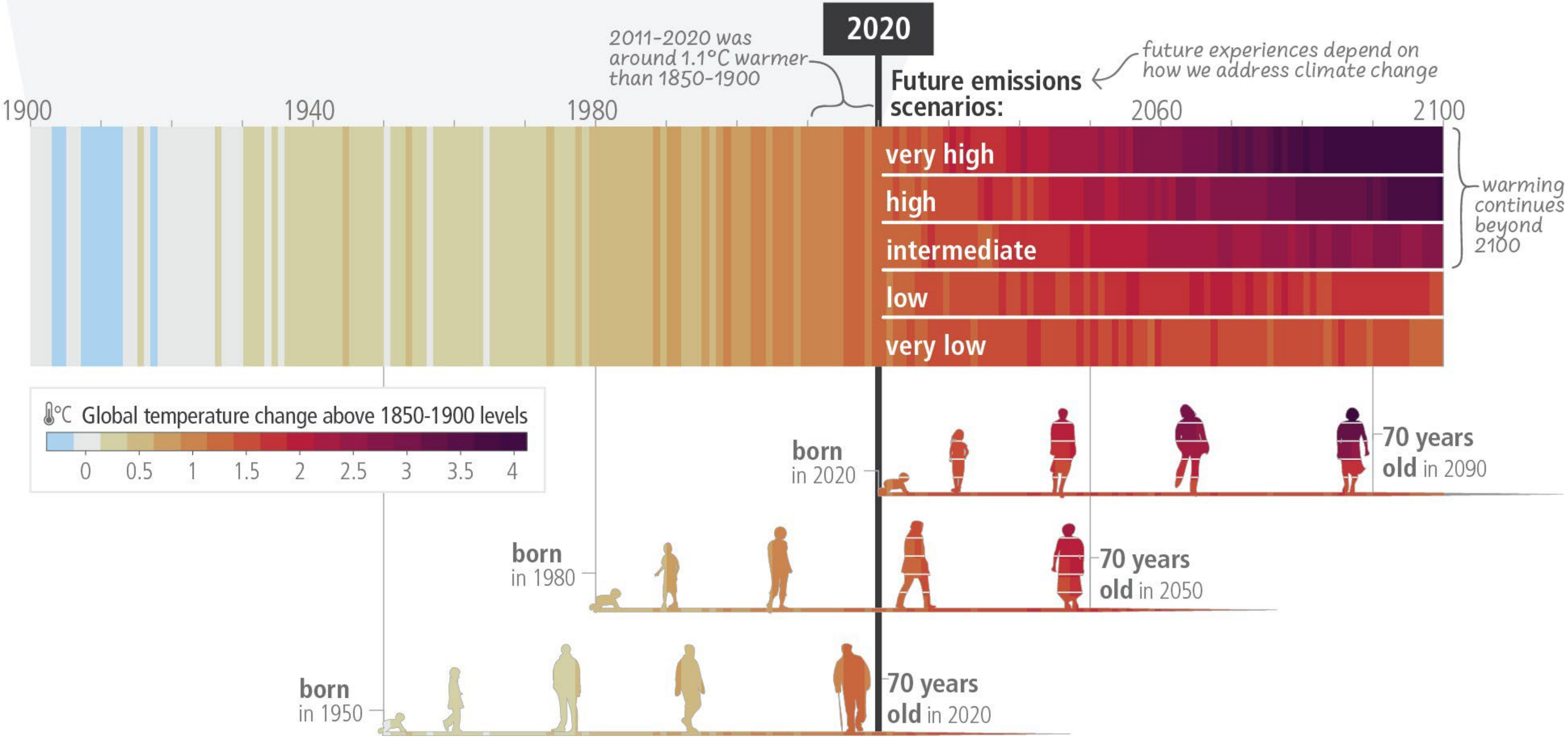


Figure from IPCC AR4 WGI SPM



Global surface temperature change
relative to 1850–1900
°C 5
4
3
2
1
0
–1
very high
high
intermediate
low
very low
shading represents the uncertainty ranges for the low and high emissions scenarios
2011-2020 was around 1.1°C warmer than 1850-1900
1950
2000
2015
2050
2100

c) **The extent to which current and future generations will experience a hotter and different world depends on choices now and in the near-term**



IPCC. AR6 Synthesis Report Summary for Policy Makers

NAVIGATE Summer School 2023

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Exploring uncertainty

with IAMs and scenarios

Picture by Jakub Kriz on Unsplash