

PRISMA Summer School 2026
*Uncertainty in energy and integrated
assessment models of climate change*

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Robust Decision Making and Scenario Discovery

1. The “Robust Decision Making” approach to uncertainty
2. Focus on “scenario discovery” methods
3. “Scenario discovery” applied to scenario ensembles from integrated assessment models of climate change

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.

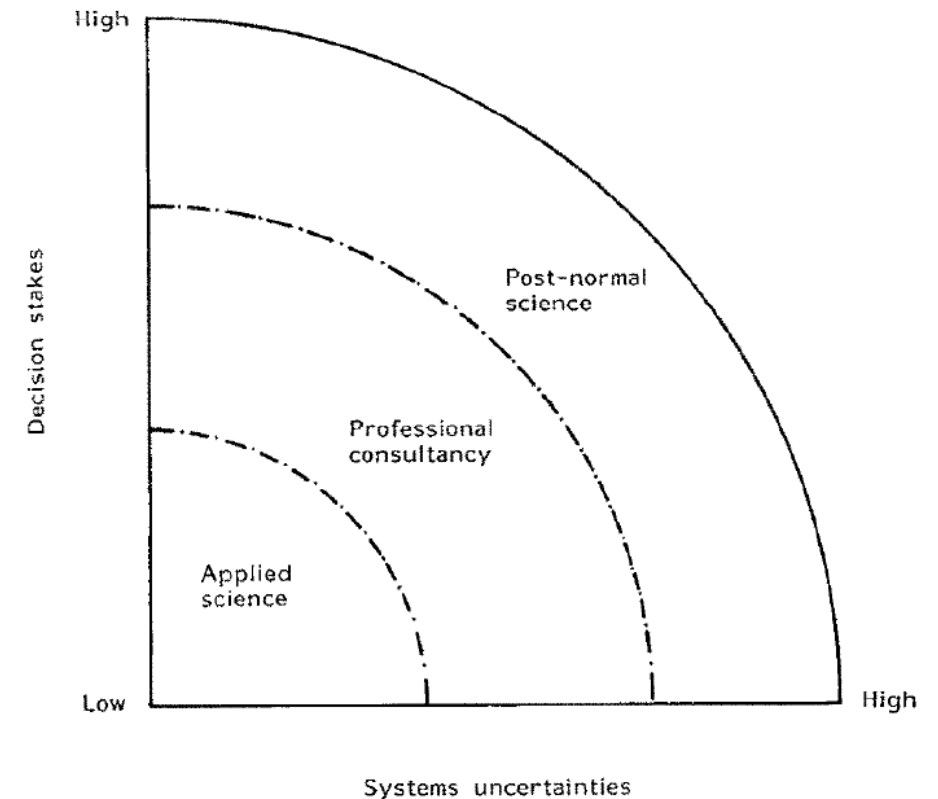
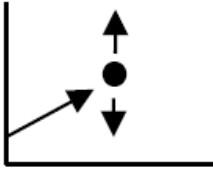
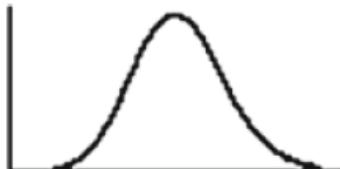
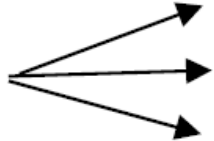
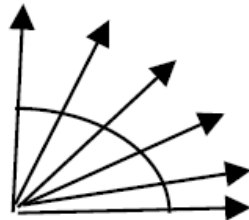
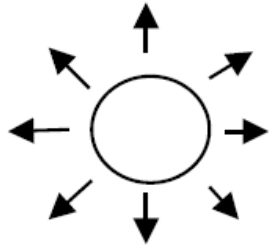


Figure 1. Problem-solving strategies

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	

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)

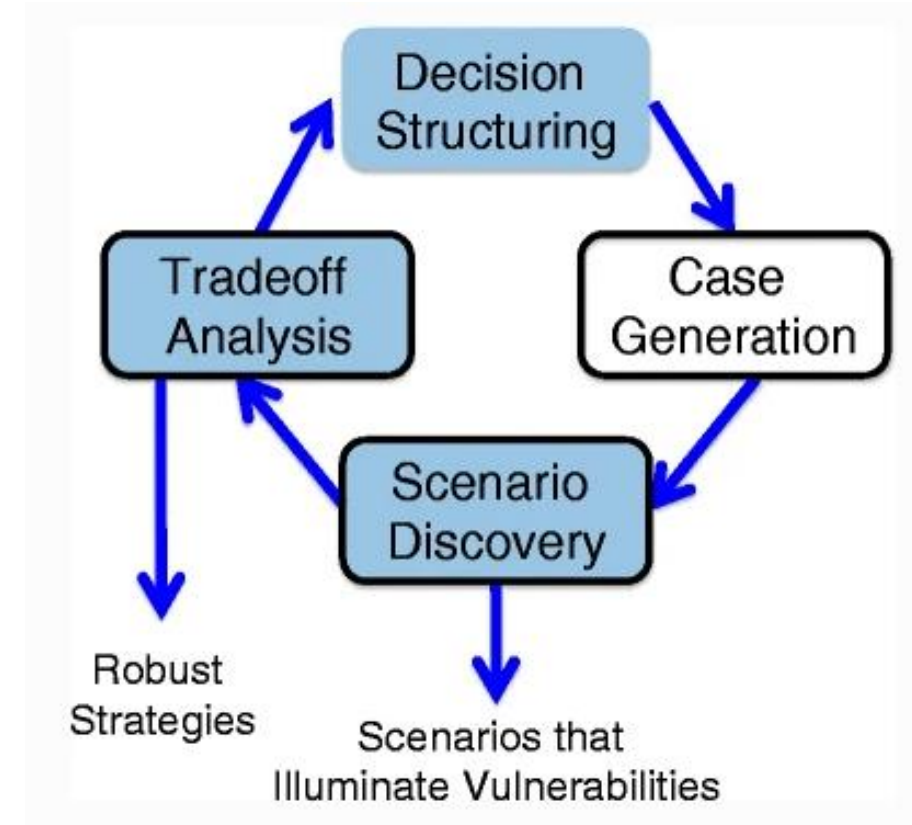
Decision making under (deep) uncertainty

- 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.

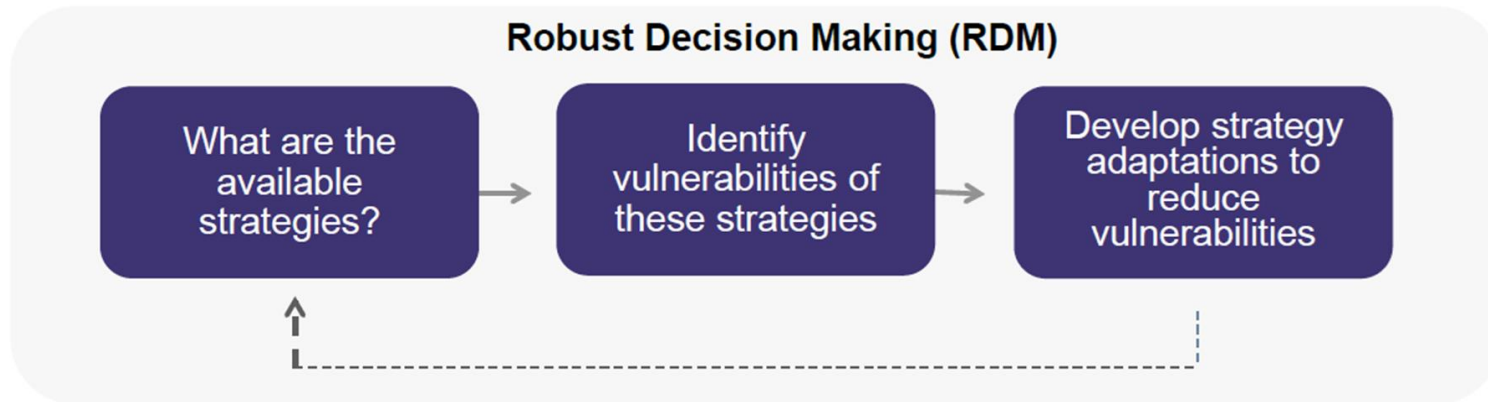
Robust Decision Making

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.



Robust Decision Making



- Consider a **multiplicity of plausible futures**, as diverse as possible to stress test proposed policies.
- Seek **robust, rather than optimal, strategies**. Robust strategies perform well, compared to the alternatives, over a wide range of plausible futures.
- Employ **adaptive strategies** to achieve robustness. Adaptive strategies are designed to evolve over time in response to new information. Generally, such strategies are organized around signposts to monitor, and contingency actions to take in response to those signposts.
- Use the computer to **facilitate human deliberation** over explorations, options, and tradeoffs, not as a device for recommending a particular ordering of strategies.

(Lempert et al. 2003)

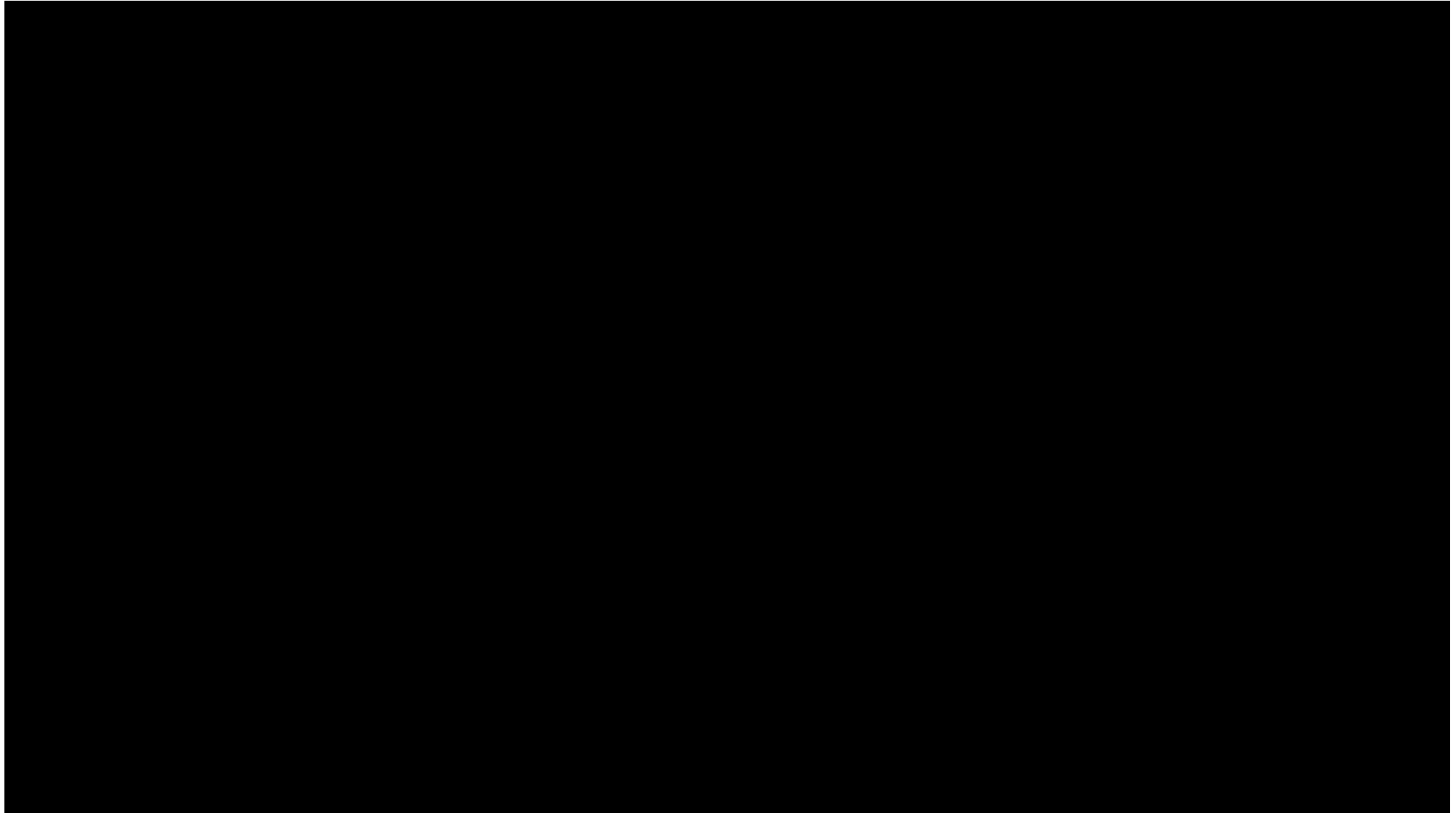
Vincent A. W. J. Marchau · Warren E. Walker ·
Pieter J. T. M. Bloemen · Steven W. Popper
Editors

Decision Making under Deep Uncertainty

From Theory to Practice



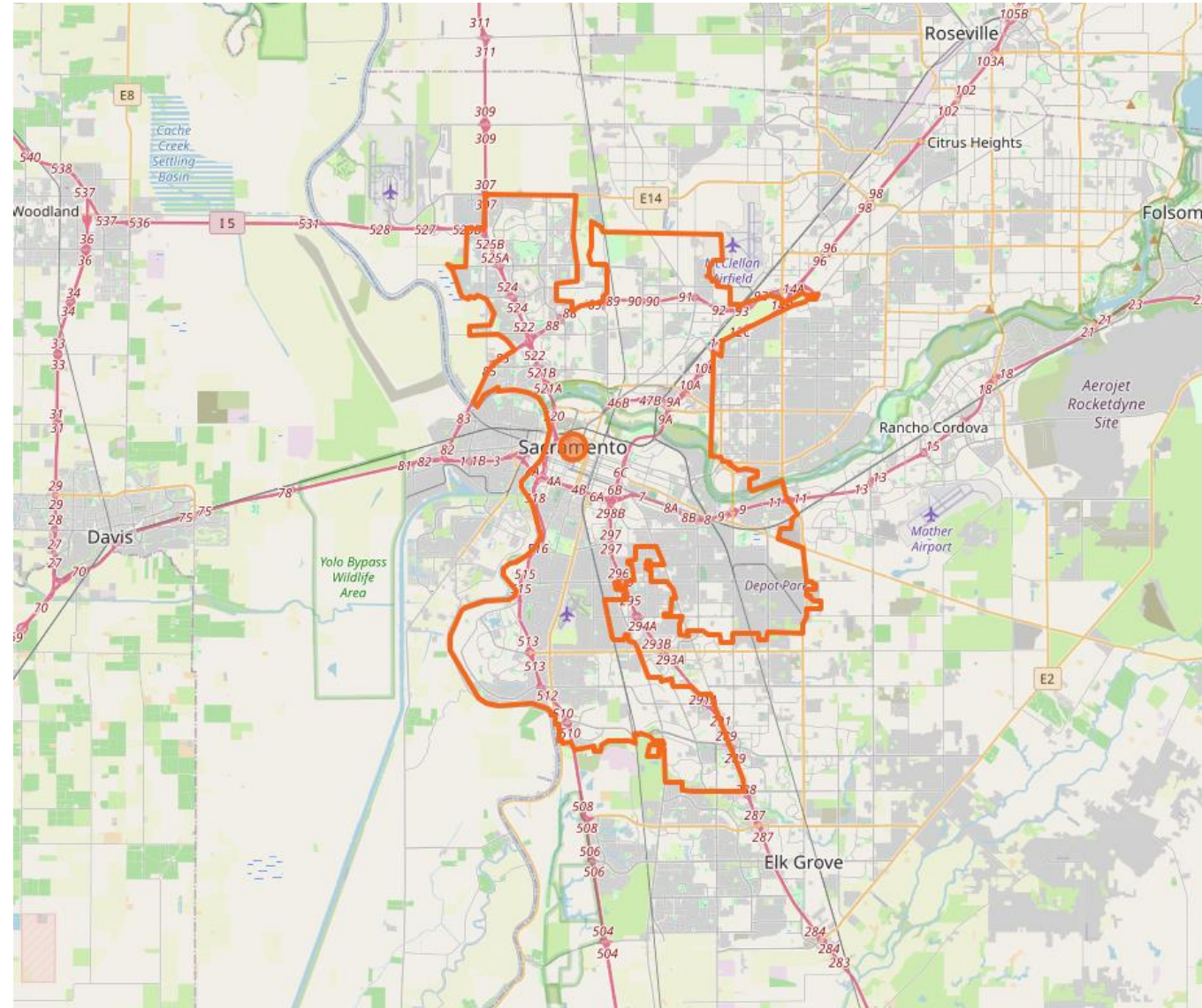
Robust Decision Making



One example: Transport planning

Lempert, et al. (2020). Meeting Climate, Mobility, and Equity Goals in Transportation Planning Under Wide-Ranging Scenarios, Journal of the American Planning Association, DOI: [10.1080/01944363.2020.1727766](https://doi.org/10.1080/01944363.2020.1727766)

How can Sacramento Area Council of Government's transportation planning meet its emissions reduction, mobility and equity goal, under uncertainty ?



One example: Transport planning

Lempert, et al. (2020). Meeting Climate, Mobility, and Equity Goals in Transportation Planning Under Wide-Ranging Scenarios, Journal of the American Planning Association, DOI: 10.1080/01944363.2020.1727766

MEASURES (GOALS)

- GHG reduction from passenger vehicles, both total and subset under California's SB 375 regulations (*total GHG emissions* and *SB 375 emissions*)
- Overall mobility as measured by person-trips for all cohorts (*mobility*)
- Equity as measured by person-trips for low- and middle-income cohorts (*equity*)

UNCERTAINTIES

- External forces, such as the price of gasoline, average fuel efficiency of internal combustion vehicles, and employment growth in the region
- Adoption of new technologies, in particular zero emission vehicles (ZEVs)
- Behavioral changes such as the preferences for driving
- The elasticity of vehicle miles traveled (VMT) with respect to the cost of driving and to employment growth

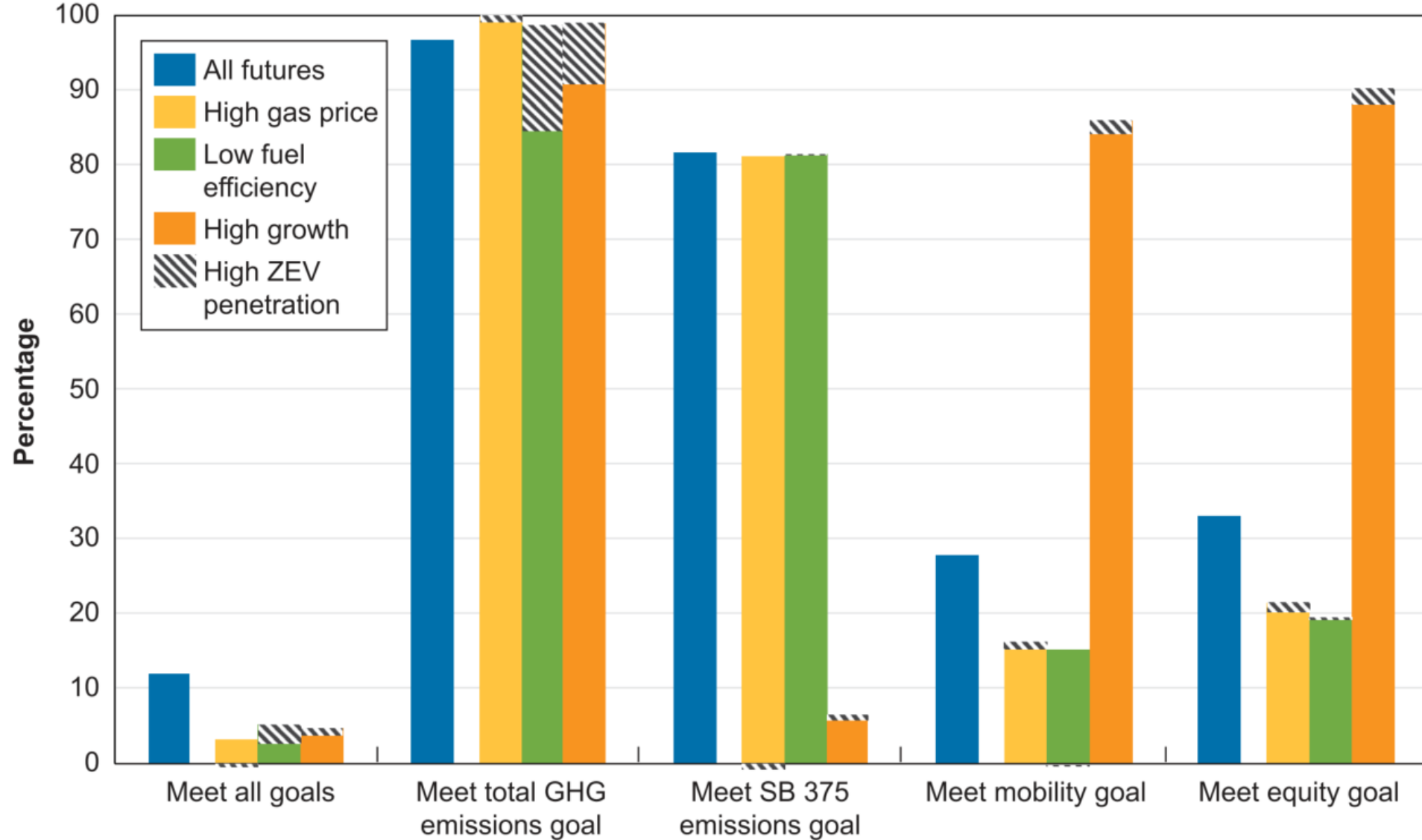
POLICY LEVERS

- Investment in maintaining existing road and rail infrastructure
- Improvements to the transit system
- Investments in multimodal transit options
- More compact development pattern and mix of land uses

RELATIONSHIPS

The SACSIM travel demand simulation model

One example: Transport planning



Fraction of futures in which the current plan meets goals in alternative scenarios.

One example: Transport planning

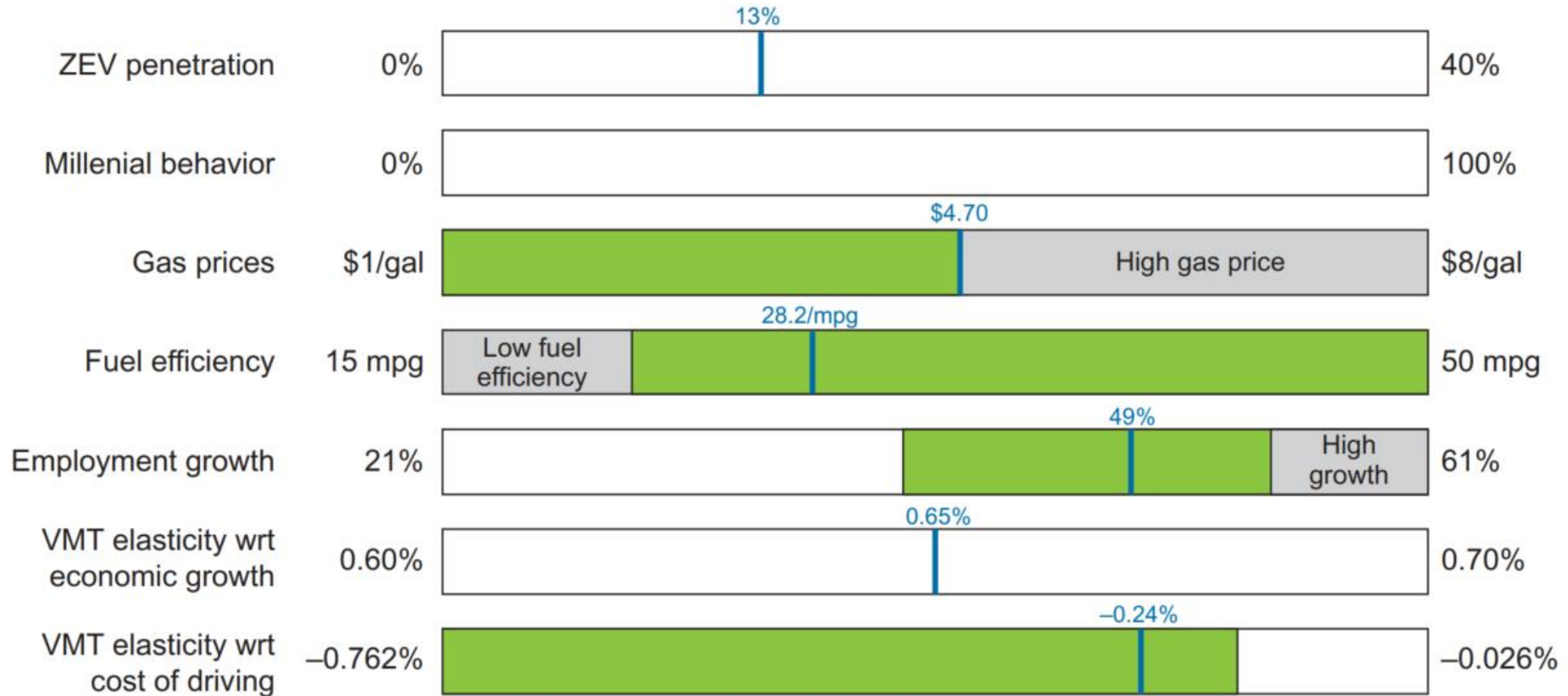


Figure 5. Key drivers for the “meet all goals” scenario. Note: Full bars show full range of values considered in stress test for each uncertainty. Green bars show parameter ranges most important in distinguishing between futures that meet and miss criteria for the meet all goals scenario. Vertical blue lines show best-estimate parameter values for 2016 SACOG MTP/SCS. Gray bars show three sets of conditions, discussed in the “Potential Responses Could Reduce Some Vulnerabilities” section, in which SACOG would miss its goals.

Some (recent) applications of Robust Decision Making in the energy/climate field

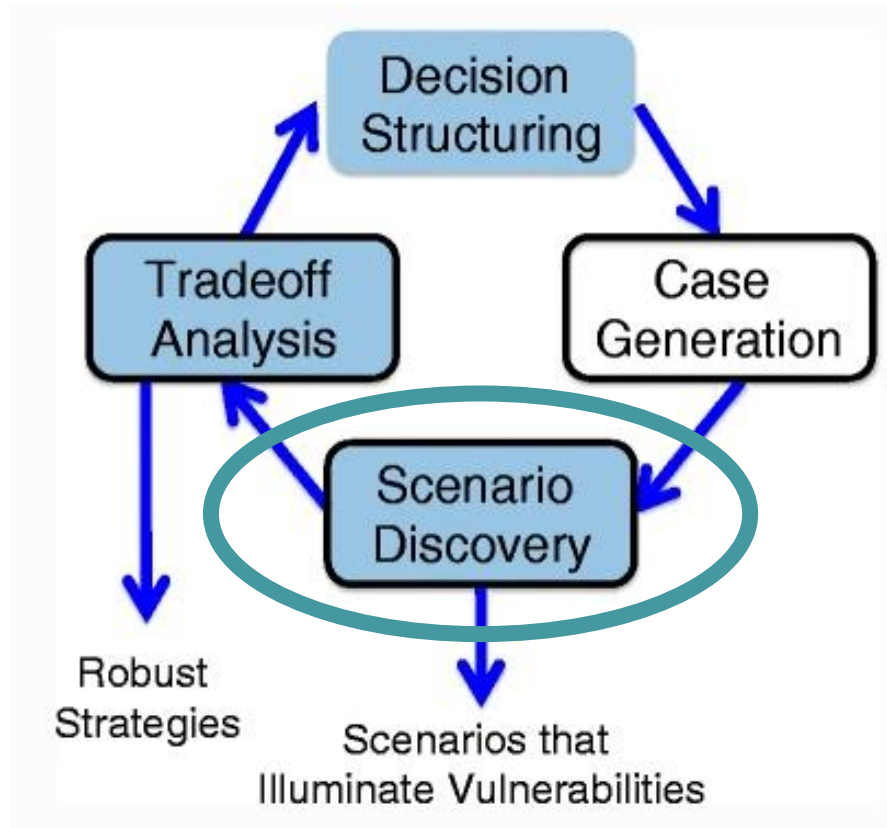
- Gambhir, Ajay, et Robert Lempert. 2023. « From Least Cost to Least Risk: Producing Climate Change Mitigation Plans That Are Resilient to Multiple Risks ». *Frontiers in Climate* 5. <https://doi.org/10.3389/fclim.2023.1149309>.
- Koponen, Kati, et Elisabeth Le Net. 2021. « Towards robust renewable energy investment decisions at the territorial level ». *Applied Energy* 287: 116552. <https://doi.org/10.1016/j.apenergy.2021.116552>.
- Lempert, Robert J., Judy Lawrence, Robert E. Kopp, et al. 2024. « The Use of Decision Making under Deep Uncertainty in the IPCC ». *Frontiers in Climate* 6 (juin). <https://doi.org/10.3389/fclim.2024.1380054>.
- Perrier, Quentin. 2018. « The second French nuclear bet ». *Energy Economics* 74: 858-77. <https://doi.org/10.1016/j.eneco.2018.07.014>.
- Rodriguez-Matas, Antonio F., Thomas B. Wild, Pedro Linares, Jonathan R. Lamontagne, et Claudia Dominguez-Barbero. 2026. « Designing robust energy policy packages under deep uncertainty: A multi-metric decision support framework ». *Energy Policy* 210: 115008. <https://doi.org/10.1016/j.enpol.2025.115008>.
- Workman, Mark, Geoff Darch, Kate Dooley, Guy Lomax, James Maltby, et Hector Pollitt. 2021. « Climate policy decision making in contexts of deep uncertainty - from optimisation to robustness ». *Environmental Science & Policy* 120: 127-37. <https://doi.org/10.1016/j.envsci.2021.03.002>.

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3. “Scenario discovery” applied to scenario ensembles from integrated assessment models of climate change

“Scenario discovery”

- Converting high-dimensional data into actionable, interpretable scenarios for research and/or decision makers.

In Robust Decision Making process



More broadly in scenario ensemble analysis

- An analytic method for translating large simulation ensembles into interpretable input regions linked to (policy-)relevant outcomes
- It works backwards to identify the model conditions (combinations of input factors) that are most strongly predictive of certain classes of results (outcomes of interest).
- This reversal of logic allows analysts to pinpoint which uncertainties matter most for a given result (e.g. policy success or failure).

“Scenario discovery” algorithms

Scenario discovery seeks regions of uncertainty space with:

- high **coverage** (captures many cases of interest),
- high **density** (few false positives),
- good **interpretability** (simple descriptions).



Criteria often in tension
Trade-offs

Two algorithms widely used:

- CART (Classification and Regression Trees) (Breiman et al., 1984)
- PRIM (Patient Rule Induction Method) (Friedman and Fisher, 1999)

CART : partitioning the uncertainty space

- "How can I recursively split the world to best predict outcomes?"

CART builds a hierarchical tree of binary splits to predict an outcome by dividing data into regions.

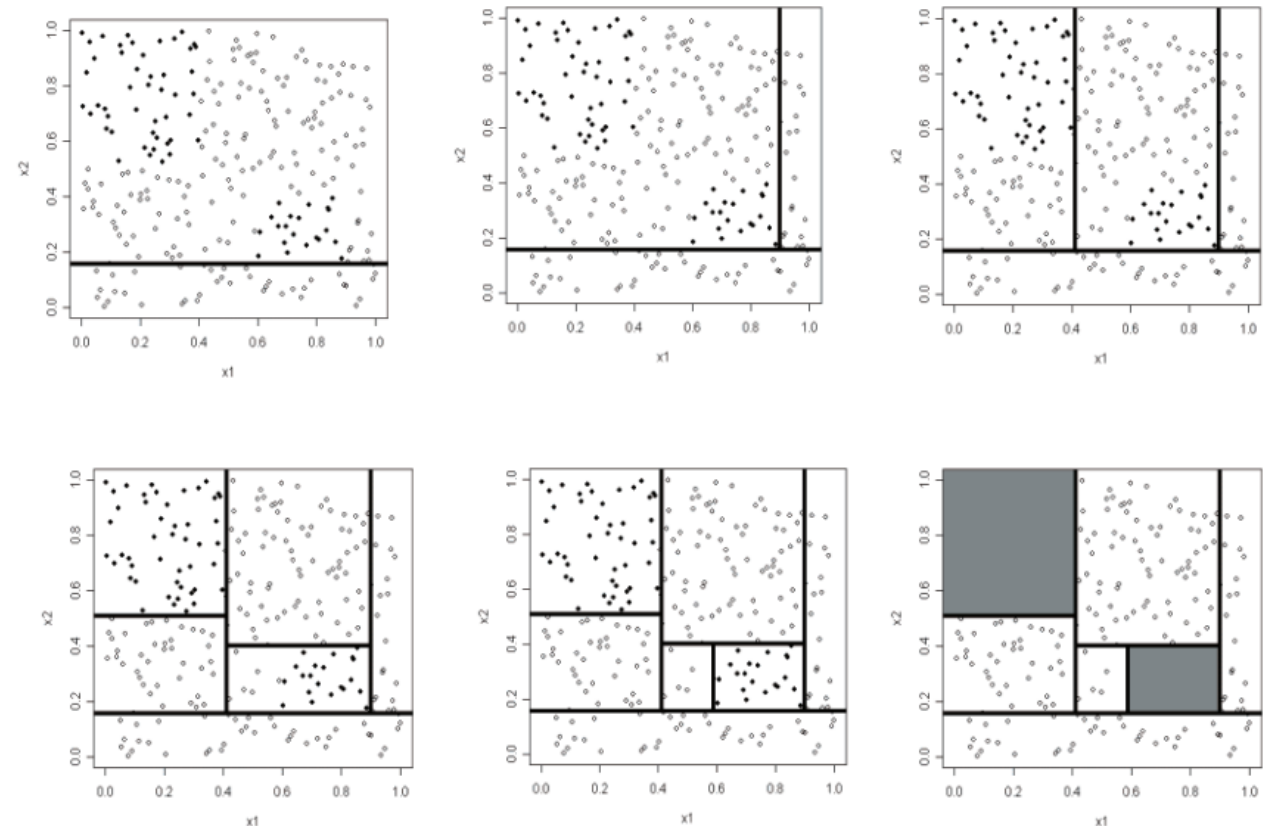
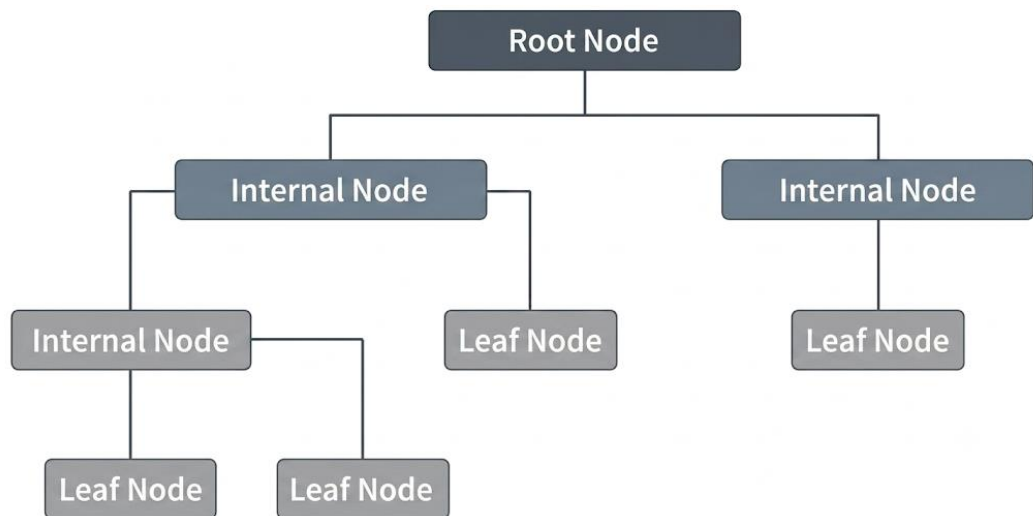


Figure 3: Conceptual illustration of CART's partitioning process

PRIM: uncovering “boxes”

- "Where are outcomes of interest concentrated, and what simple box(es) describes it?"

PRIM looks for small subregions in high-dimensional space where the outcomes of interest are concentrated.

Unlike CART, which partitions everything, PRIM searches for "needles in the haystack", local clusters of high density.

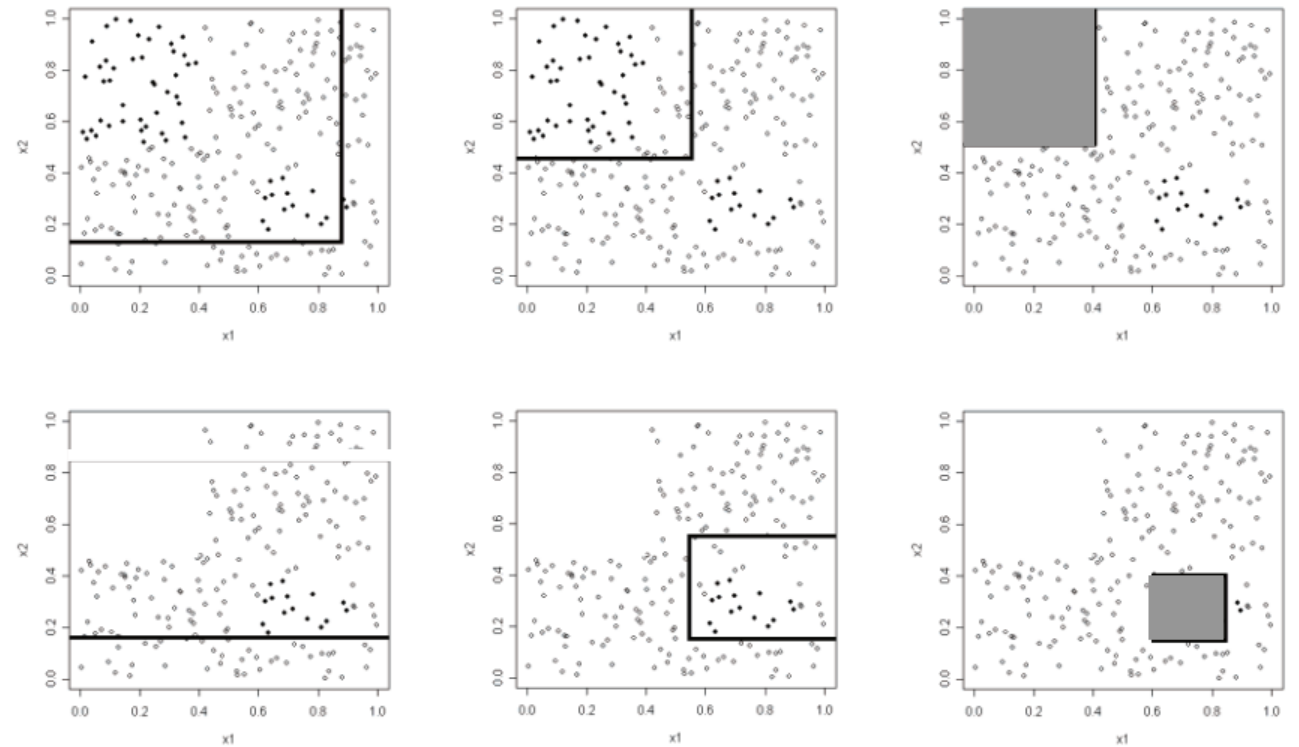
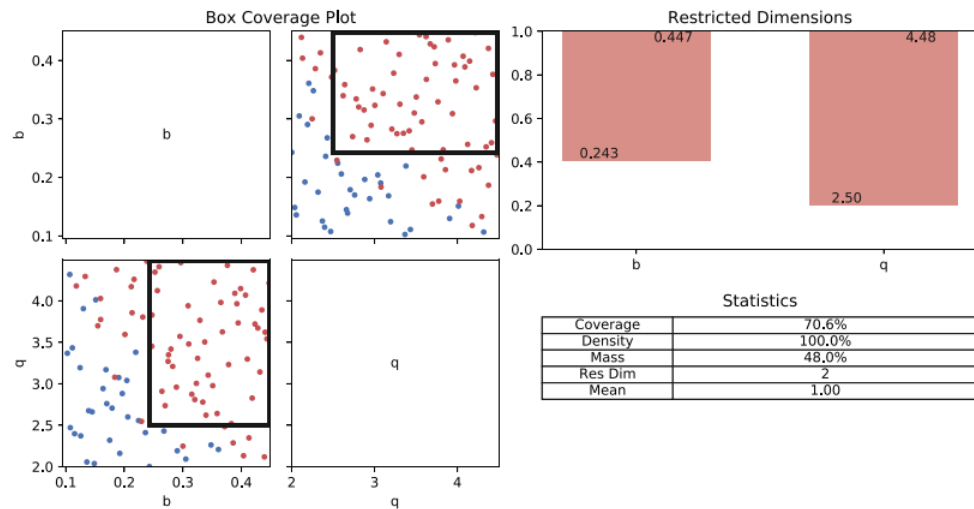


Figure 2: Conceptual illustration of PRIM's: a) peeling and b) covering process.

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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) [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)

Example 1

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>.



RESEARCH QUESTION

- What sorts of futures could lead to high emissions ?



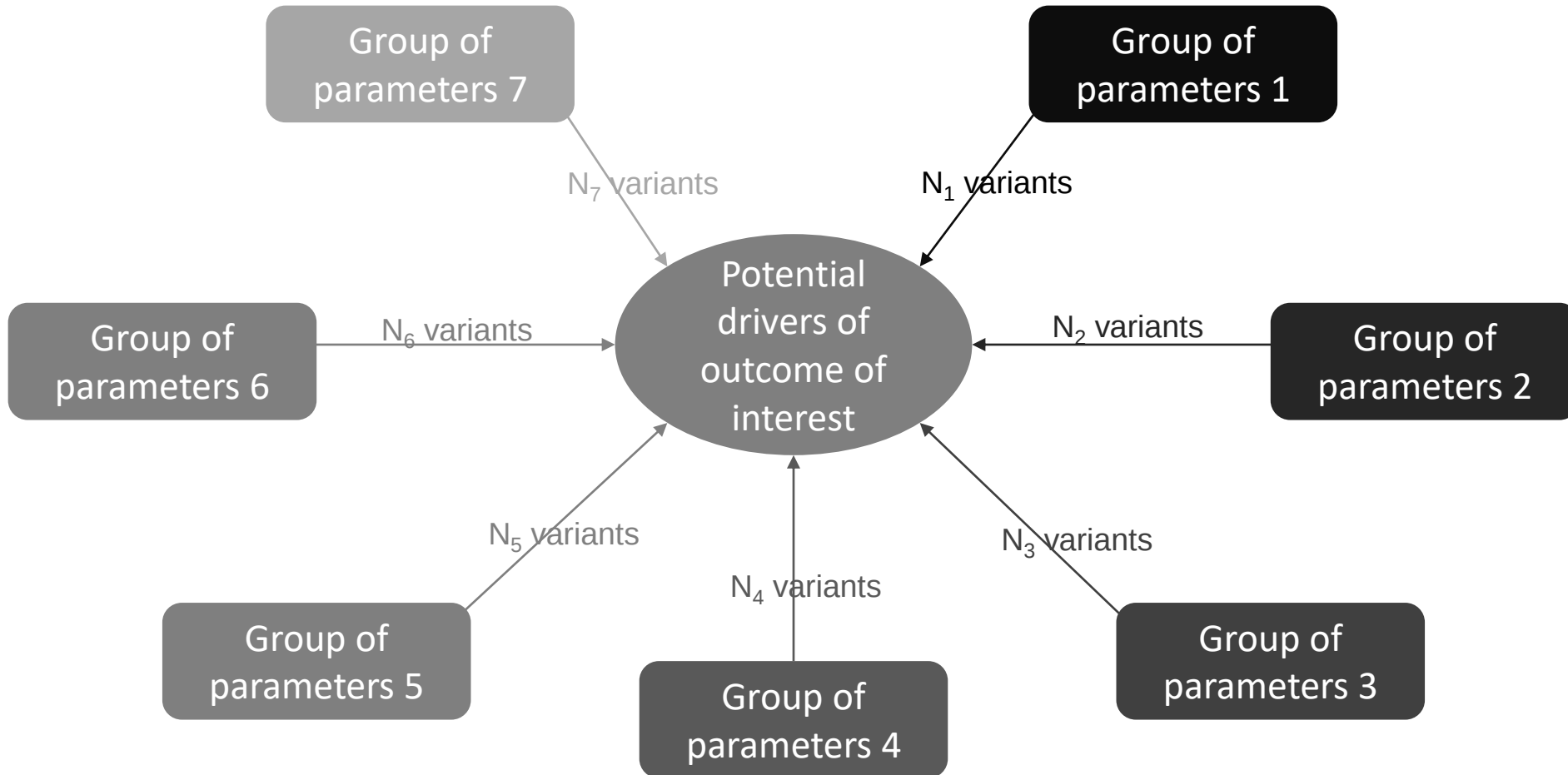
METHODS

- Constructing (structured) ensembles of scenarios, with the systematic combination of discrete sets of parameters variants (with the Imaclim-R model)
- Analyzing the ensemble to:
 - Uncover assumptions that lead scenarios to specific decision-relevant outcomes or vulnerabilities [scenario discovery approach]
 - Applied to the space of high emissions outcomes.

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

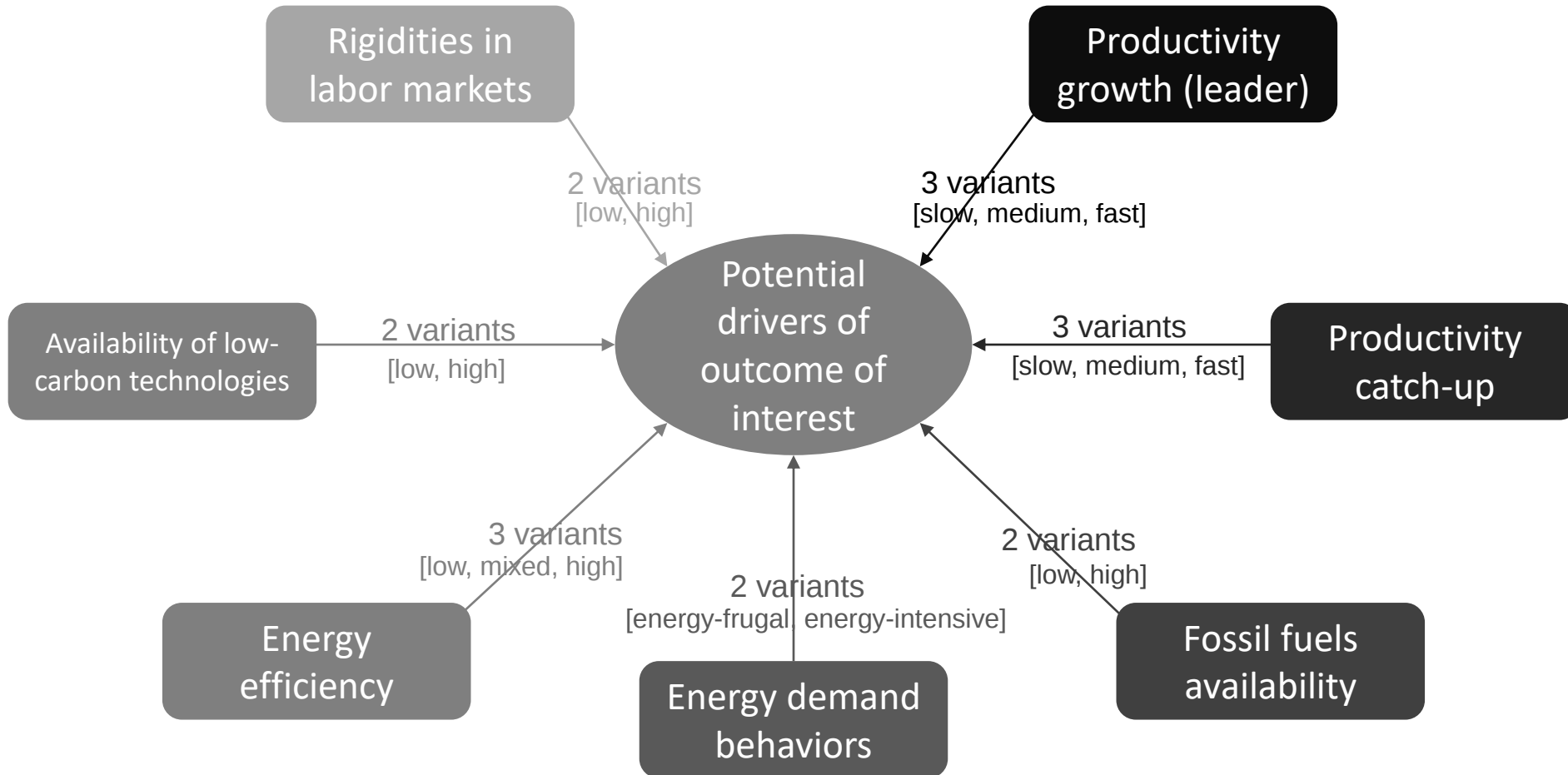
Potential
drivers of
outcome of
interest

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

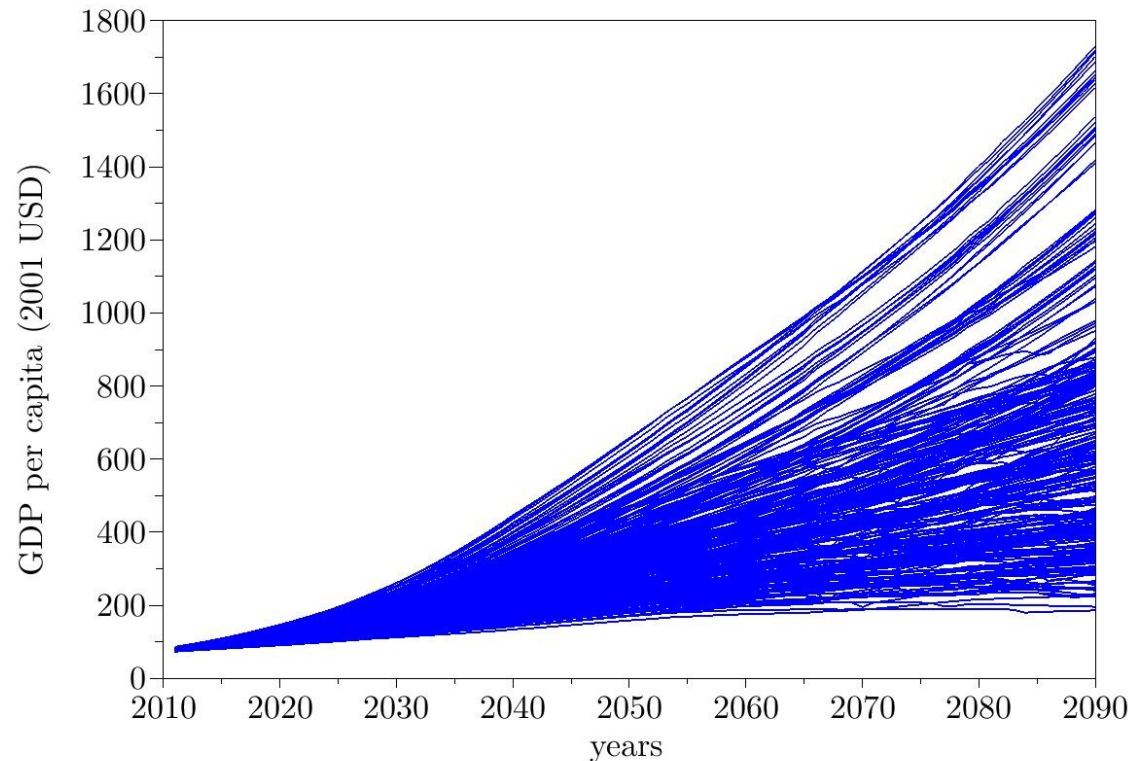


➤ 432 Imaclim-R model runs (“baseline” scenarios)

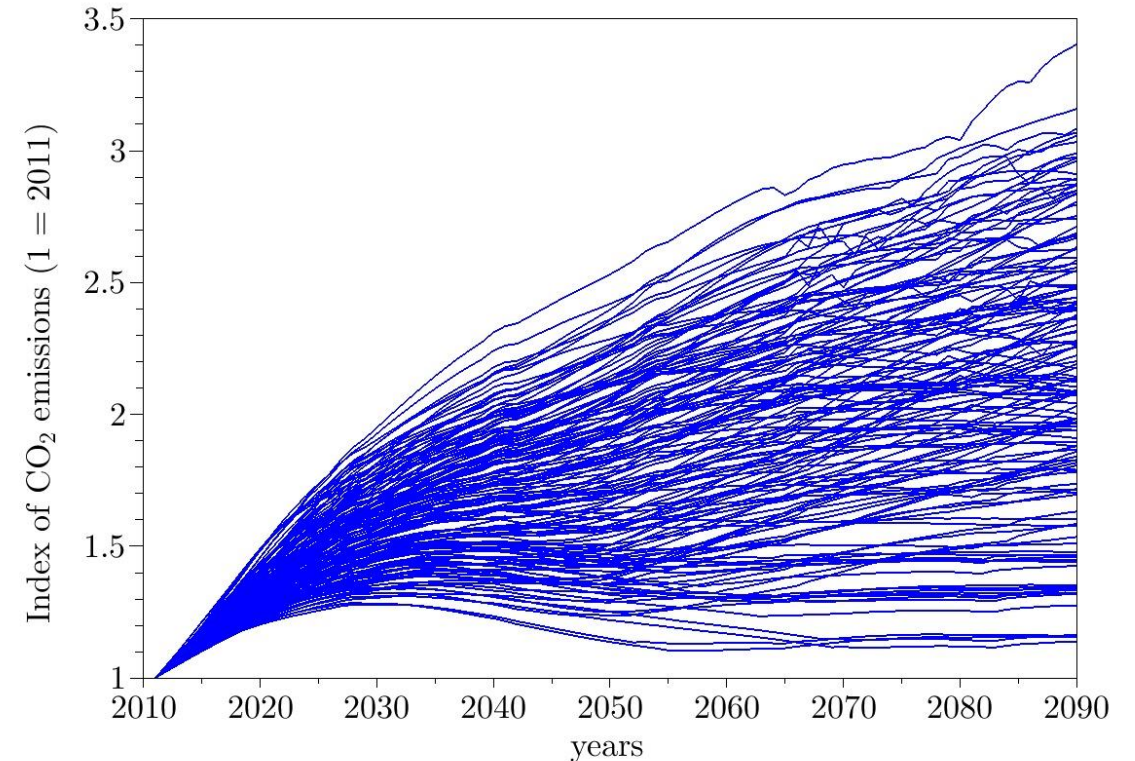
Constructing (structured) ensembles of scenarios,
with the systematic combination of discrete sets of parameters variants

Some illustrative results (extractions from the scenario ensemble)

GDP per capita of the 20% poorest in developing countries in 286 scenarios

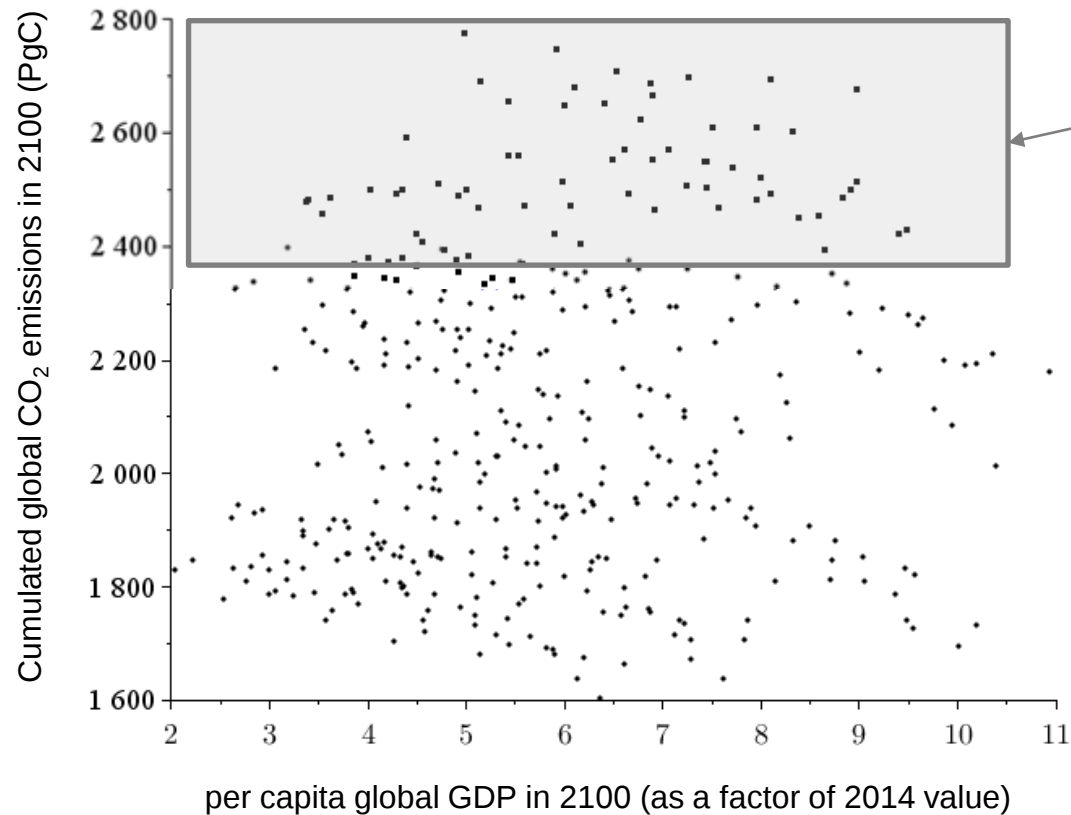


CO₂ emissions (index) for 143 baseline scenarios



? 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 CO₂ emissions in 2100 (Y-axis).

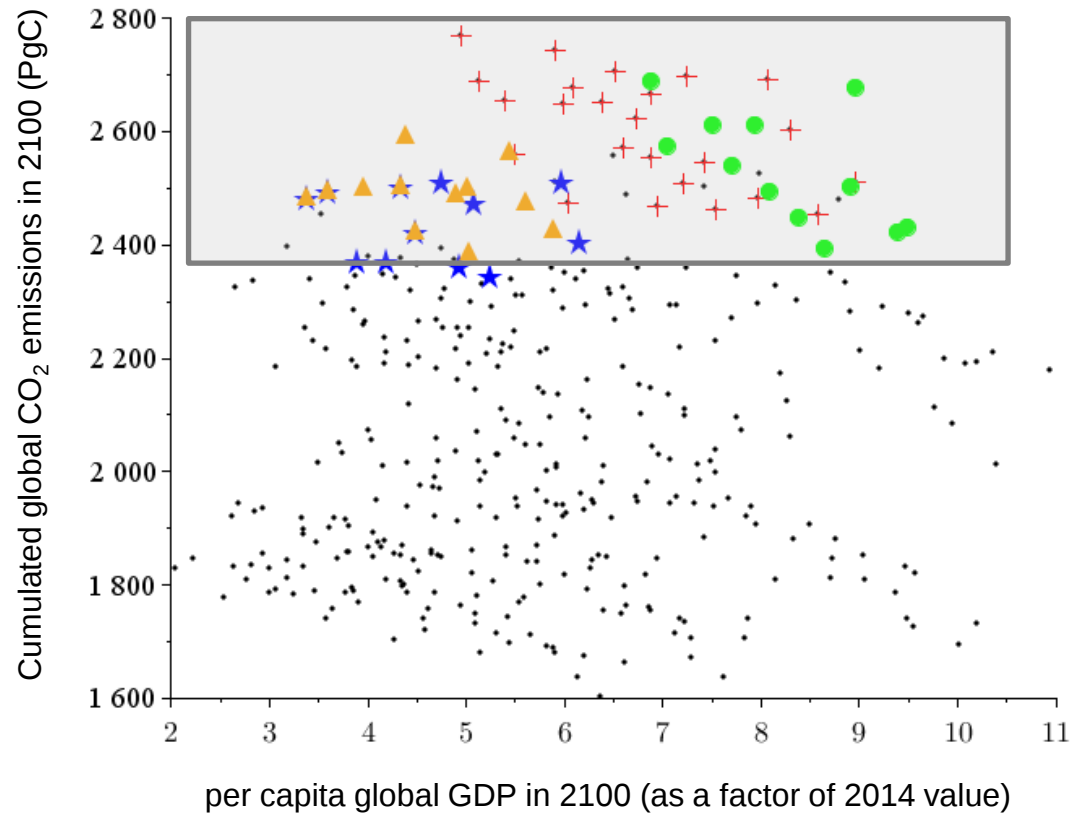


“Scenario discovery” algorithm (PRIM)* to uncover which combinations of input parameters variants lead to high emissions.

* 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/quaque/EMAworbench>

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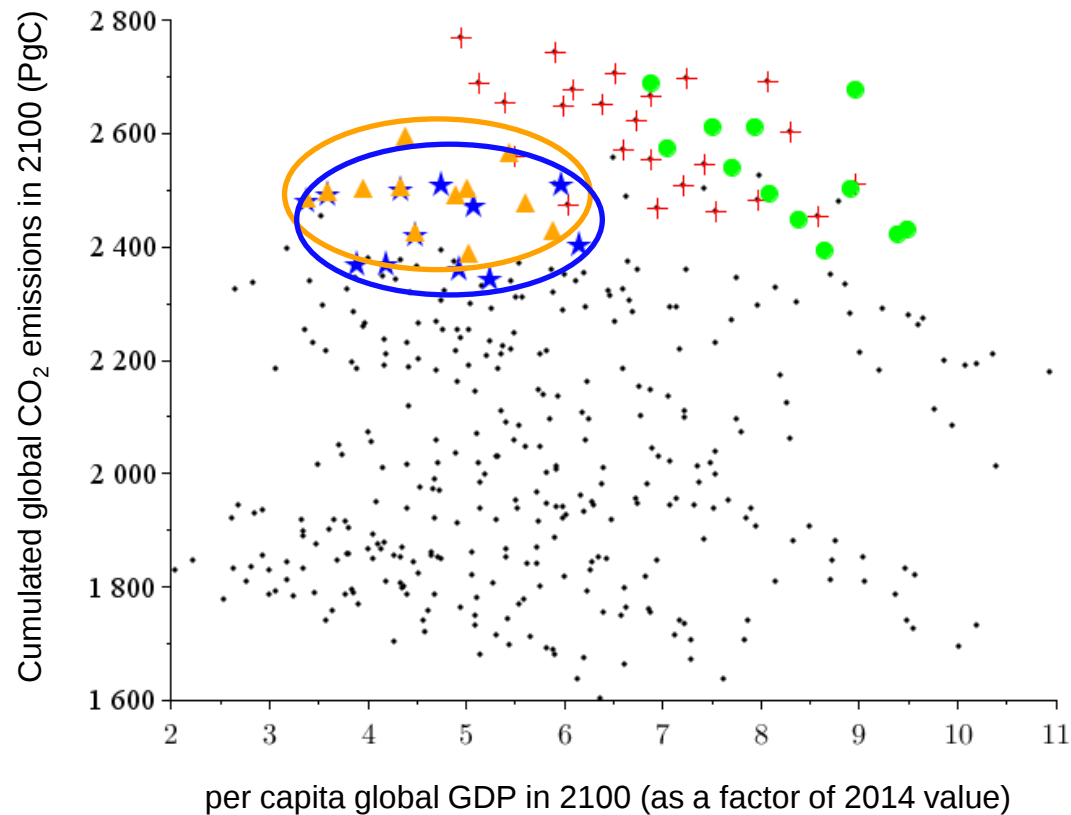
Families of scenarios with high emissions uncovered by the scenario discovery analysis.

		+	★	●	▲
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.

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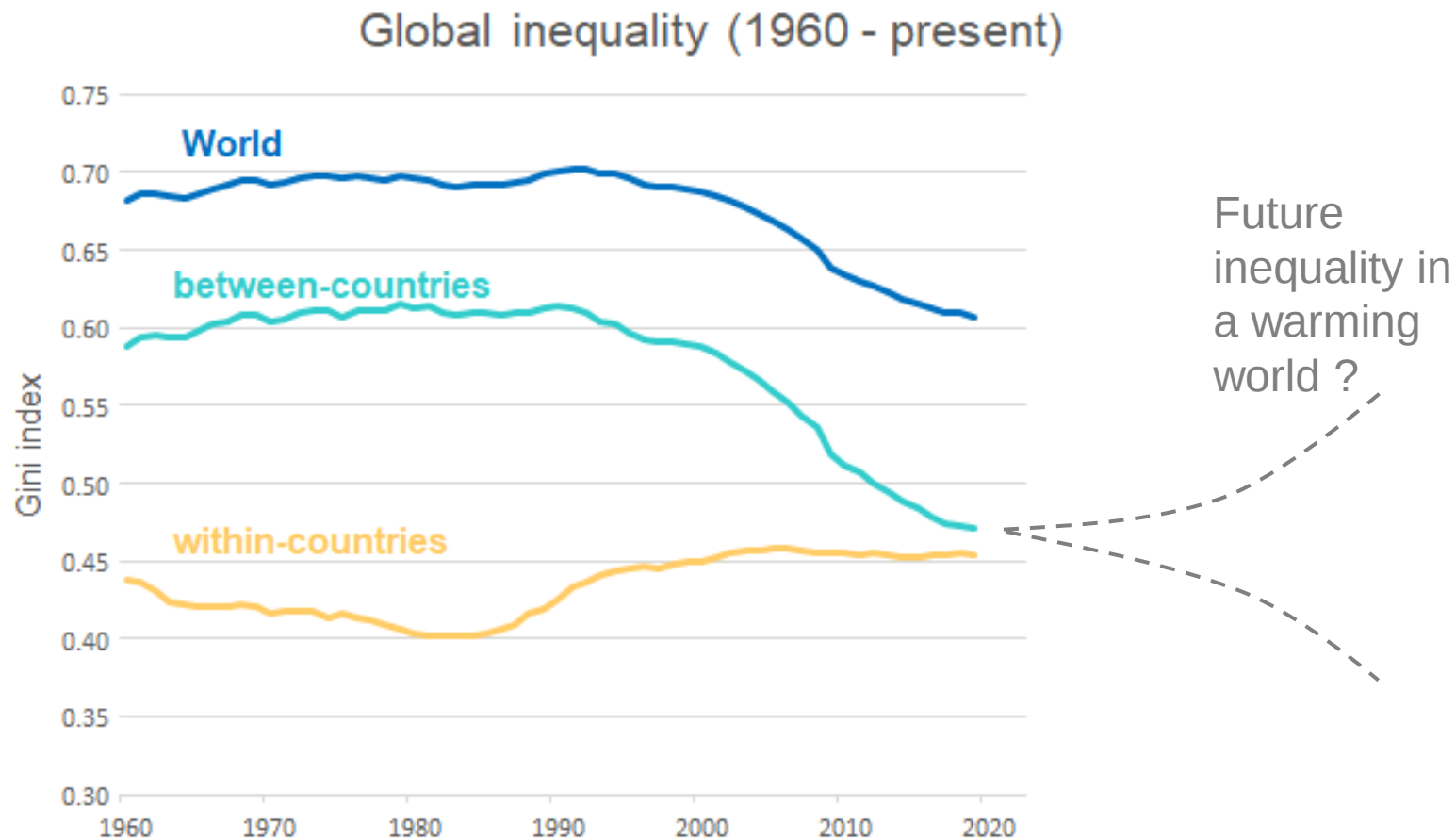
The grey boxes represent the combinations of parameters values corresponding to each family of scenarios identified.

Example 2

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 prospects for future inequality between countries under climate change?



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



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?



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

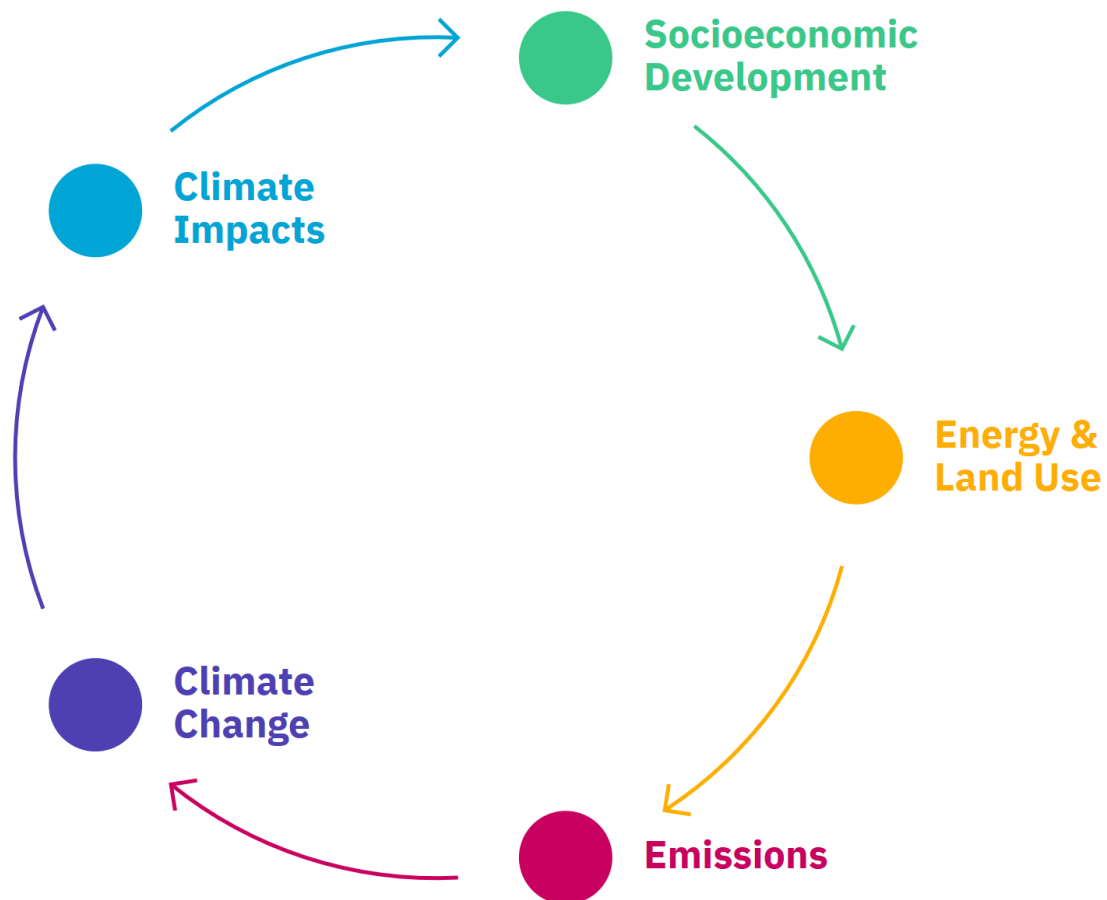
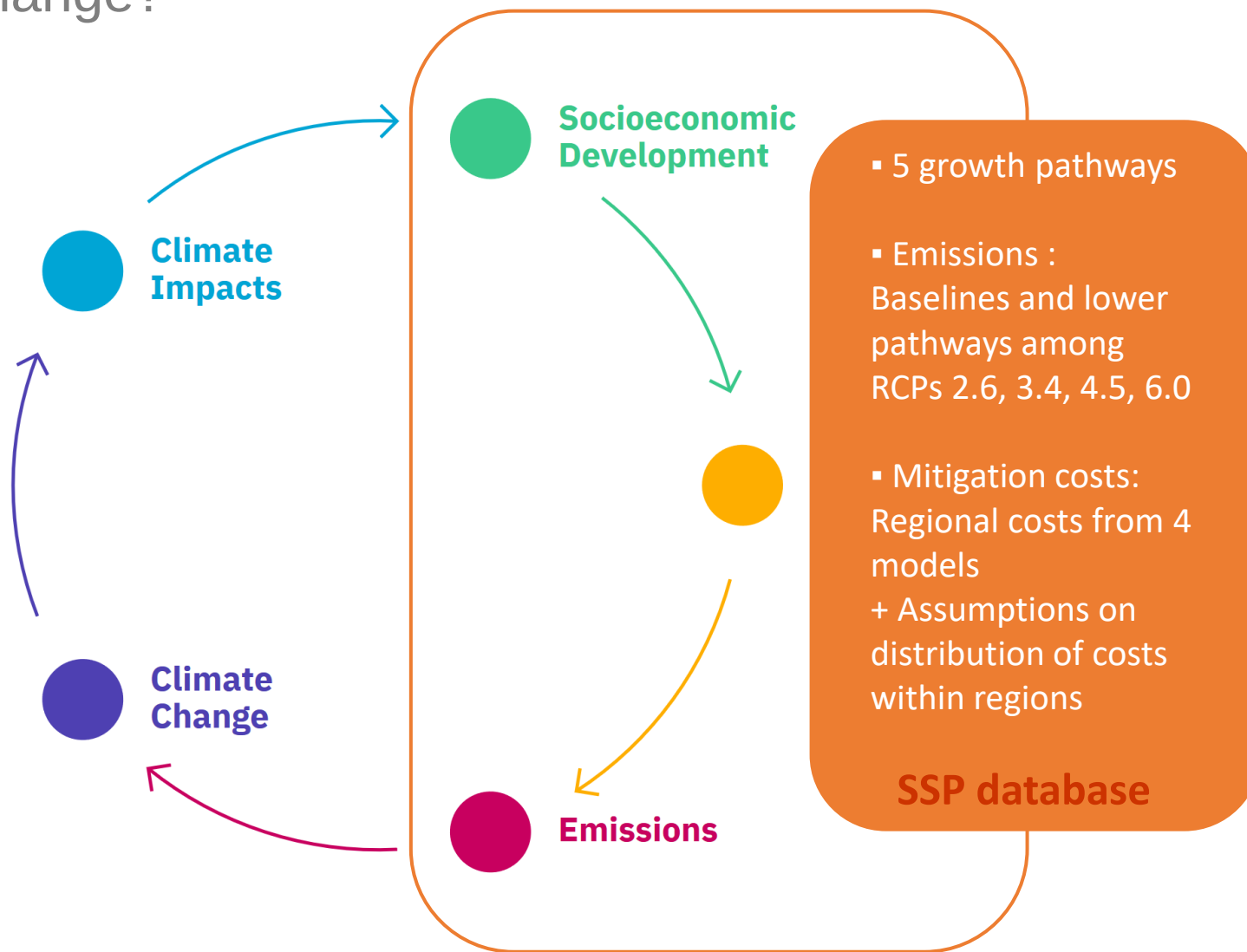


Chart from SENSES project, Scenario Primer <https://climatescenario.org/primer>

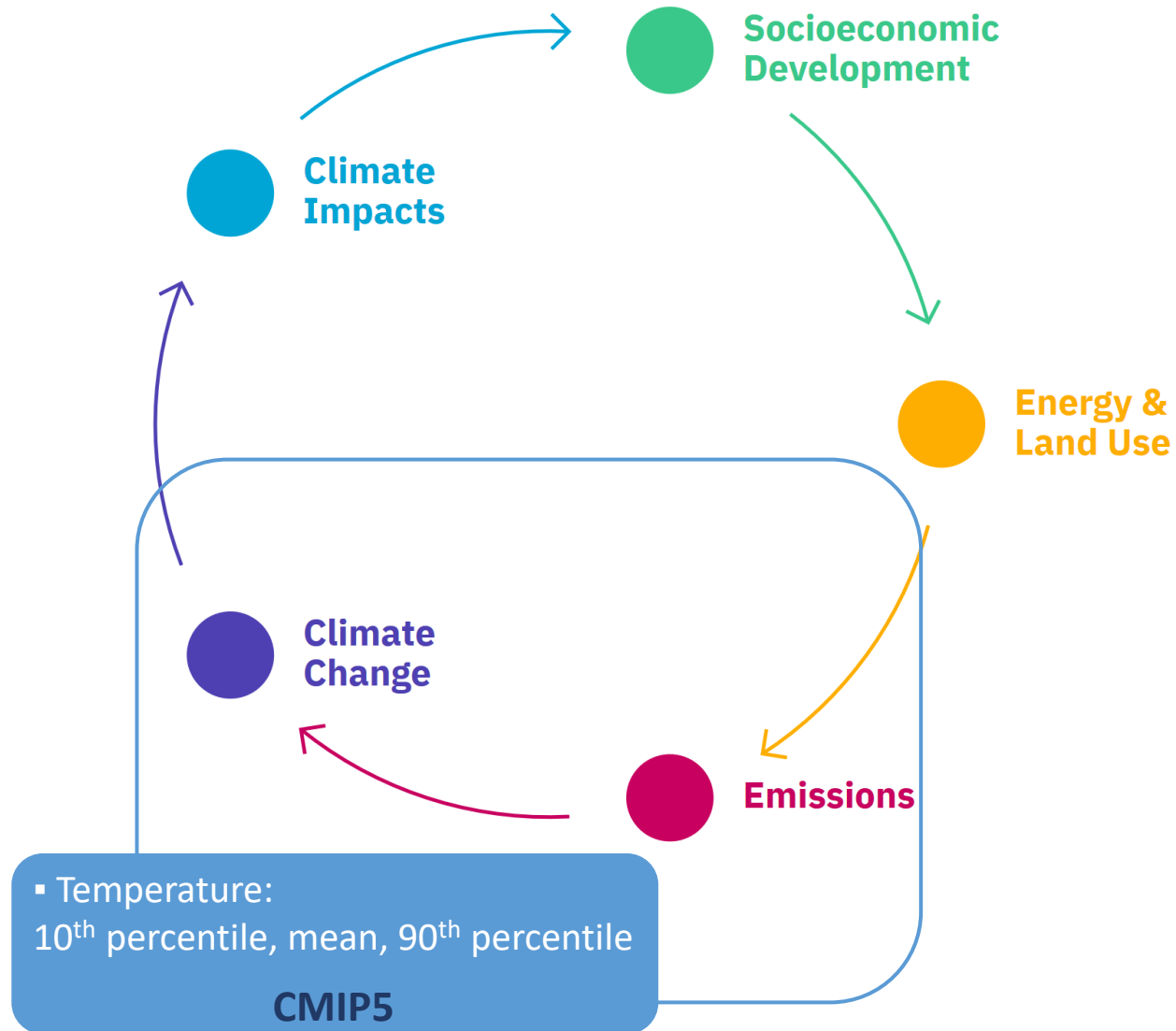


What are the prospects for future inequality between countries under climate change?



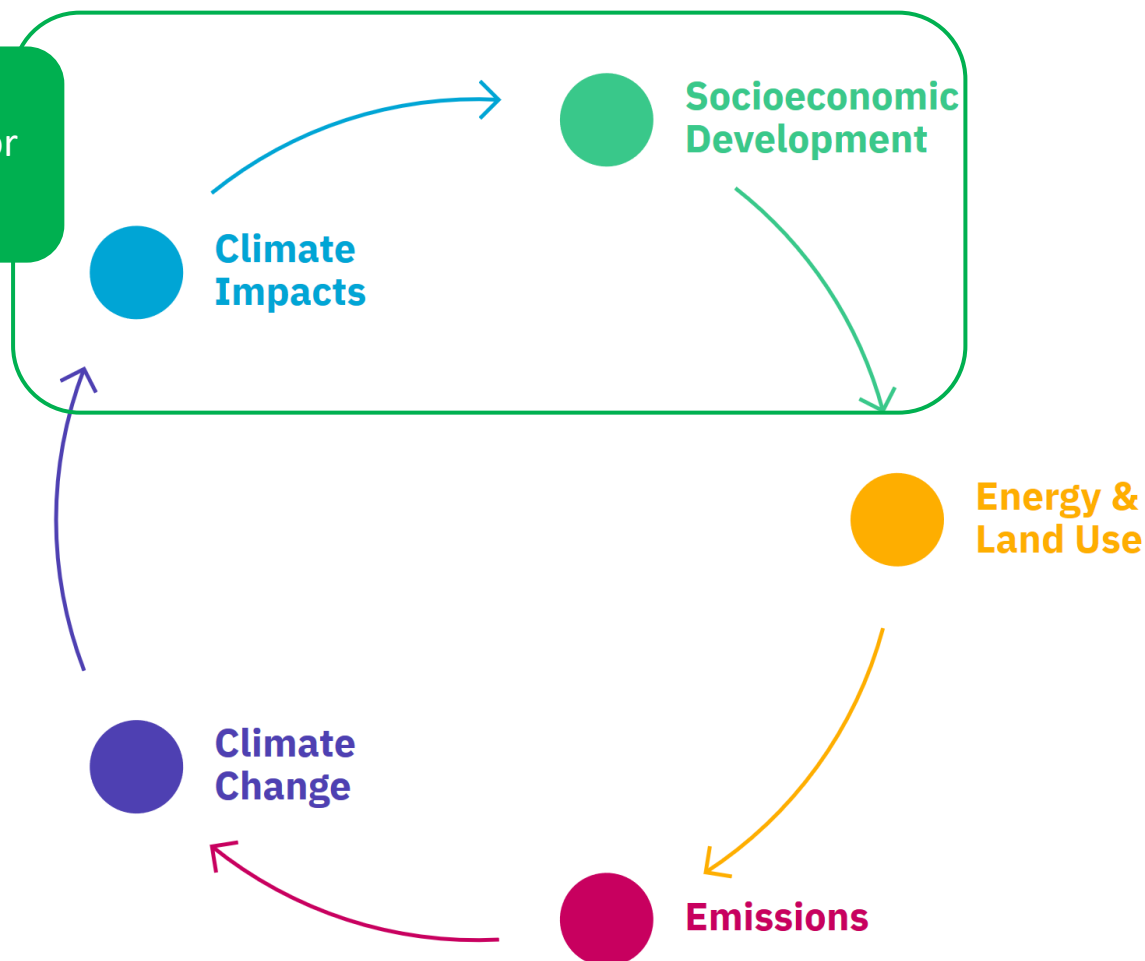


What are the prospects for future inequality between countries under climate change?



? 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?

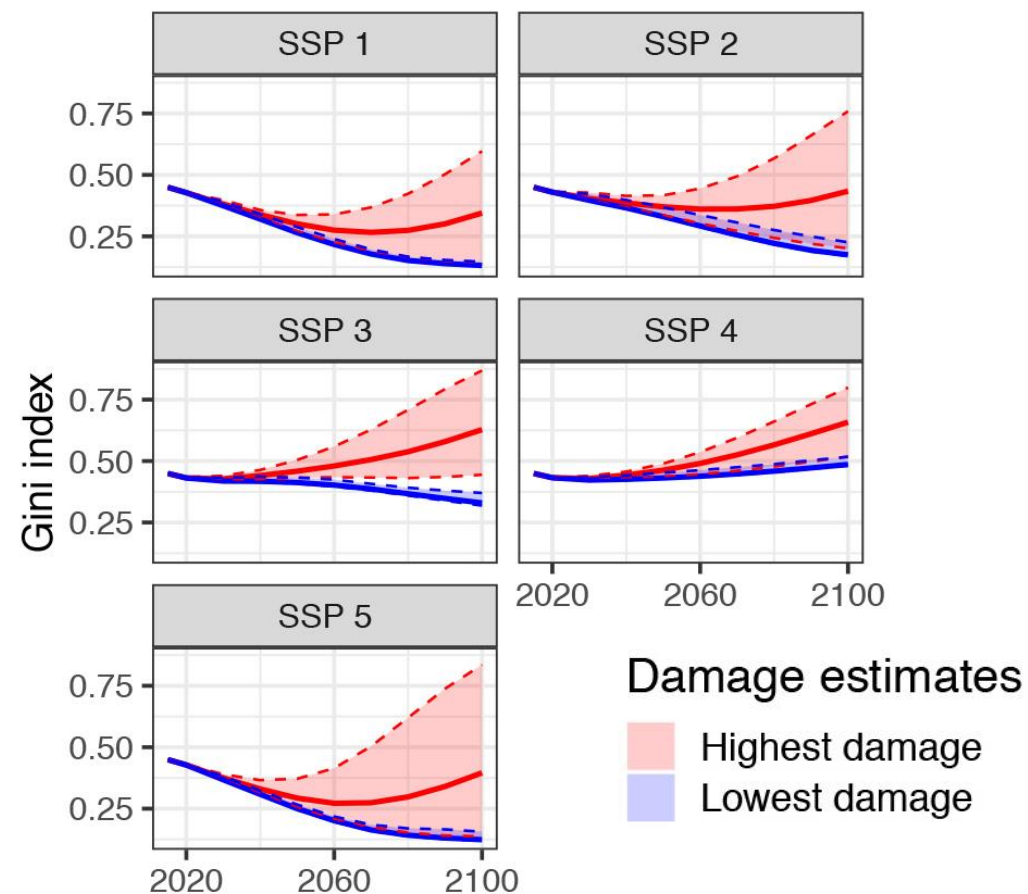


Figure from
www.carbonbrief.org/guest-post-climate-change-could-reverse-falling-inequality-between-countries

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



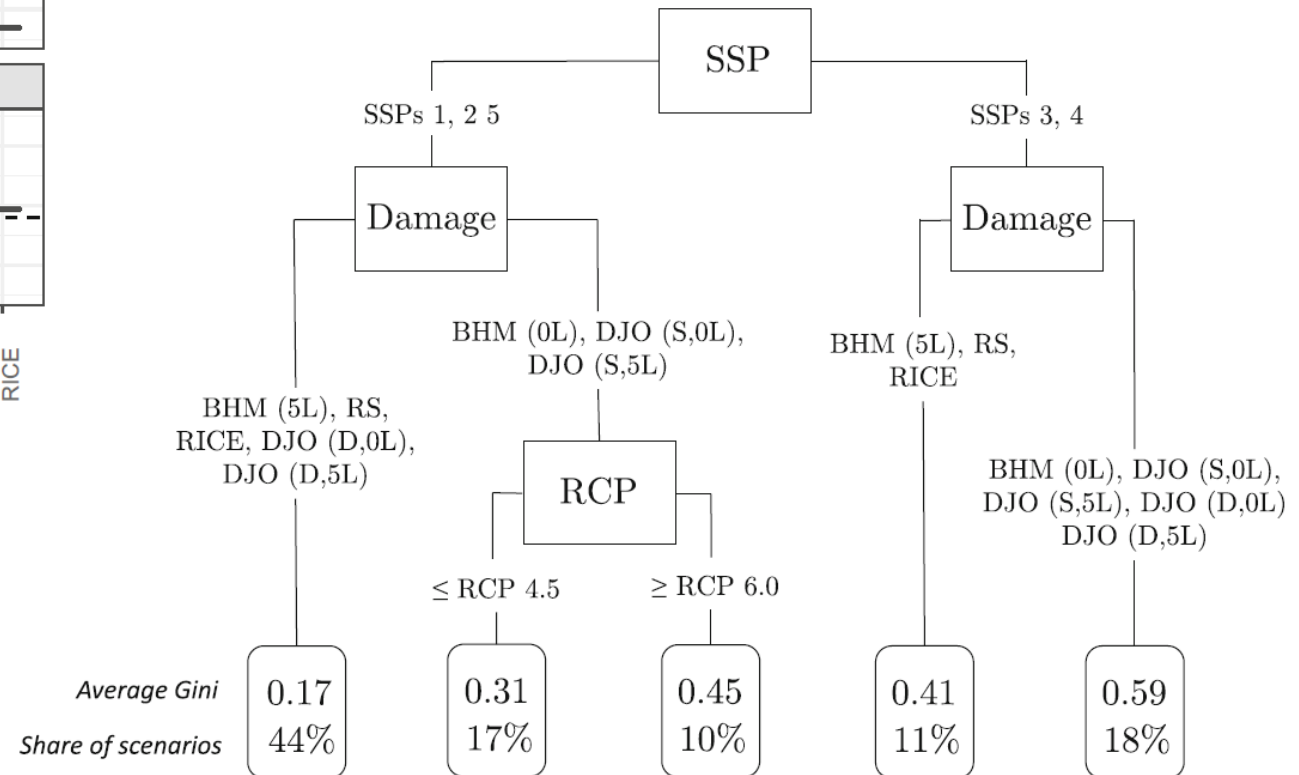
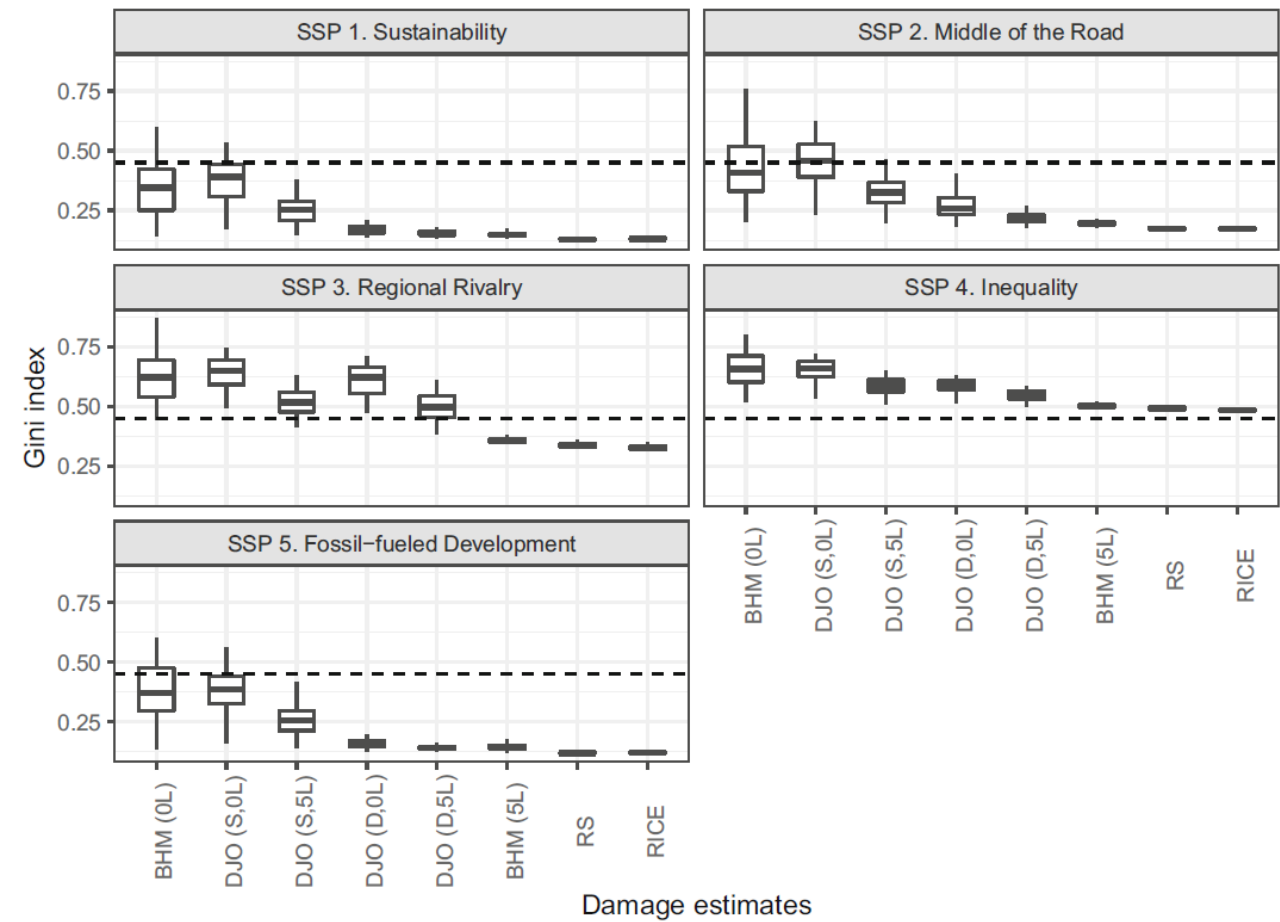
What are the prospects for future inequality between countries under climate change?

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

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



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



Example 3

Achakulwisut, Ploy, Peter Erickson, Céline Guivarch, Roberto Schaeffer, Elina Brutschin, Steve Pye (2023). **Global fossil fuel reduction pathways under different climate mitigation strategies and ambitions**. Nature Communucations 14:5425.
<https://doi.org/10.1038/s41467-023-41105-z>.



RESEARCH QUESTIONS

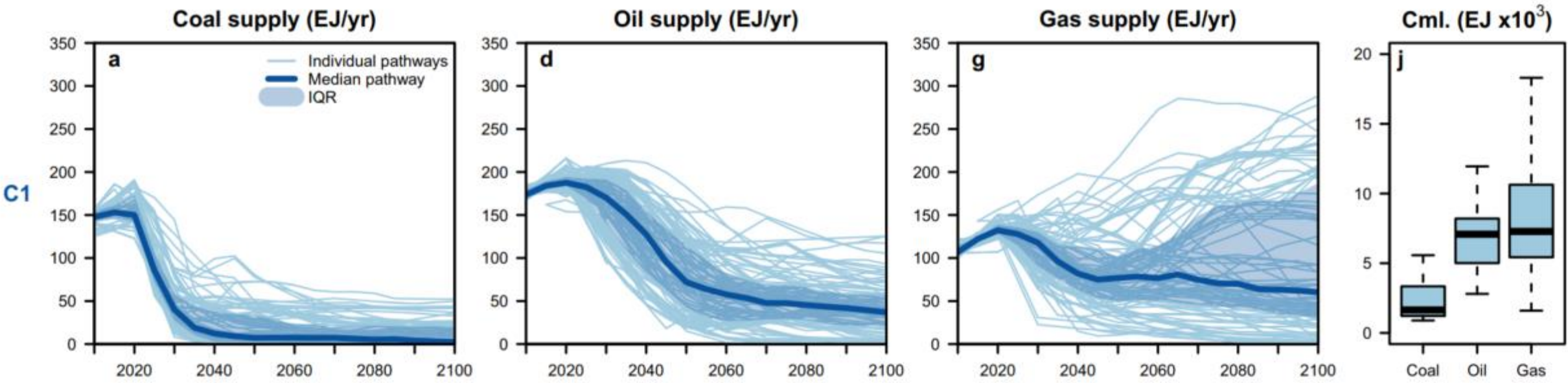
- What fossil fuel reduction pathways are consistent with limiting warming to 2° C or below ?



METHODS

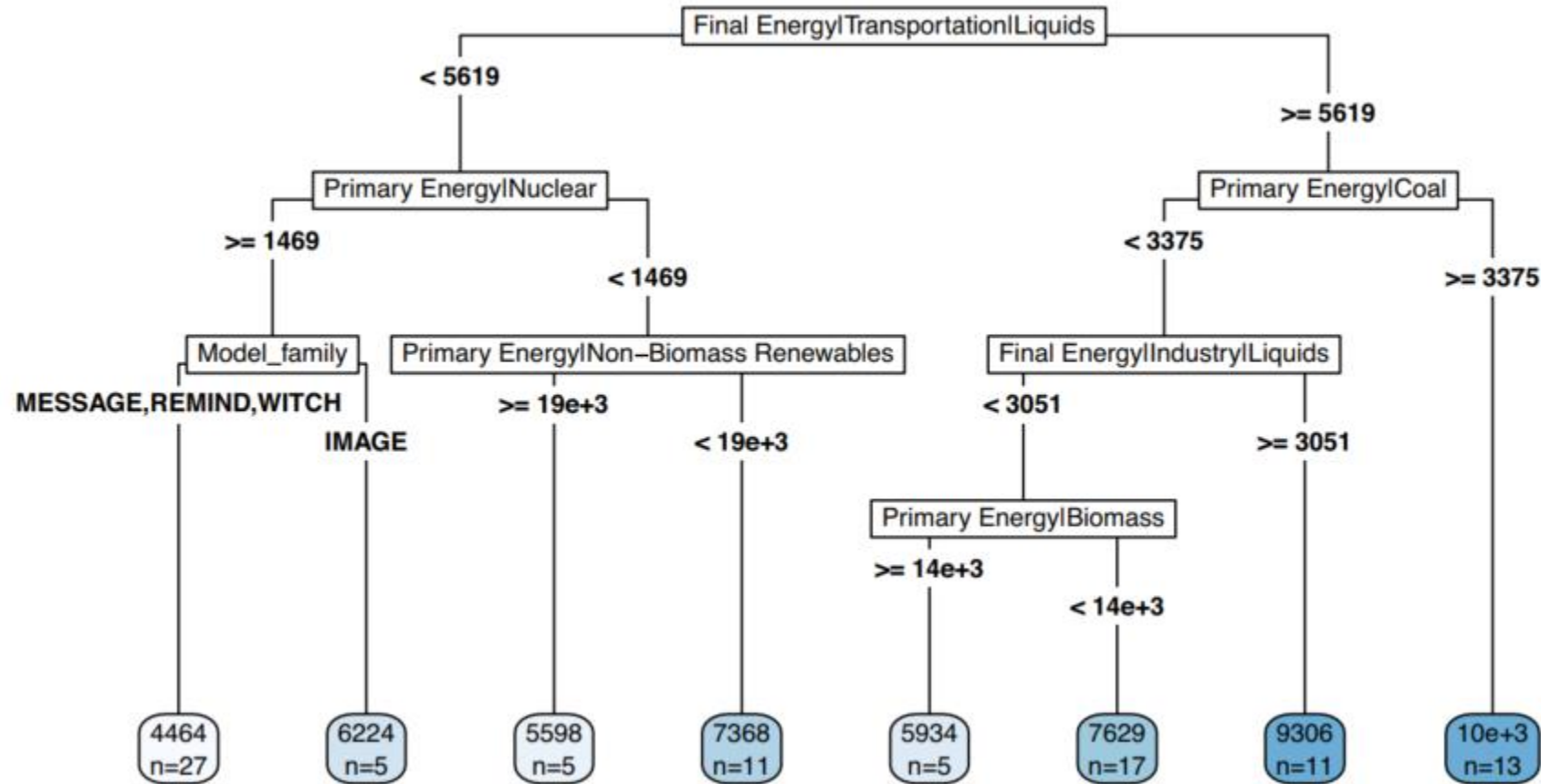
- Analyze IPCC AR6 ensemble of scenarios
- Filter with expert judgement on limits of CDR
- Analyze main factors determining fossil fuels levels
- Compare with fossil fuel producers extraction plans

Global primary energy supply from coal, oil, and gas as modelled by the AR6-assessed mitigation scenarios consistent with limiting warming to 1.5 °C with no or limited overshoot



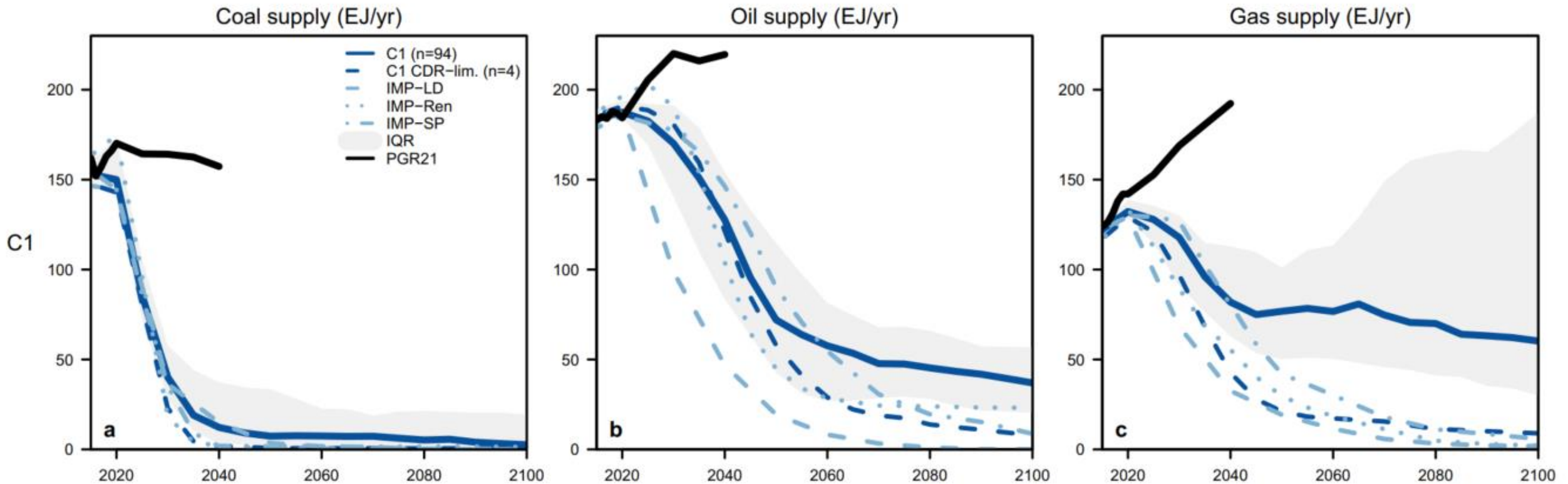
Classification and regression tree (CART) analysis results for predicting the 2020–2100 cumulative oil supply in the C1 scenarios.

CART decision tree for 2020-2100 cumulative oil supply in C1 scenarios



The blue boxes at the bottom show the average value of cumulative oil (in exajoules) across the scenarios included within each given “leaf node” (note that they do not necessarily appear in increasing order from left to right). The units of the independent variables shown are exajoules for primary and secondary energy, and million tonnes of CO₂ for emissions and carbon sequestration (negative AFOLU emissions represent CO₂ removal). Cumulative 2020–2100 values are also used for the independent variables.

2015–2100 global pathways of fossil fuel supply consistent with limiting warming to 1.5 °C with no or limited overshoot and compared to those based on government plans and projections.



Global pathways of primary energy supply (in exajoules, EJ) from coal, oil, and gas under different subsets of or individual C1 pathways as denoted inset:

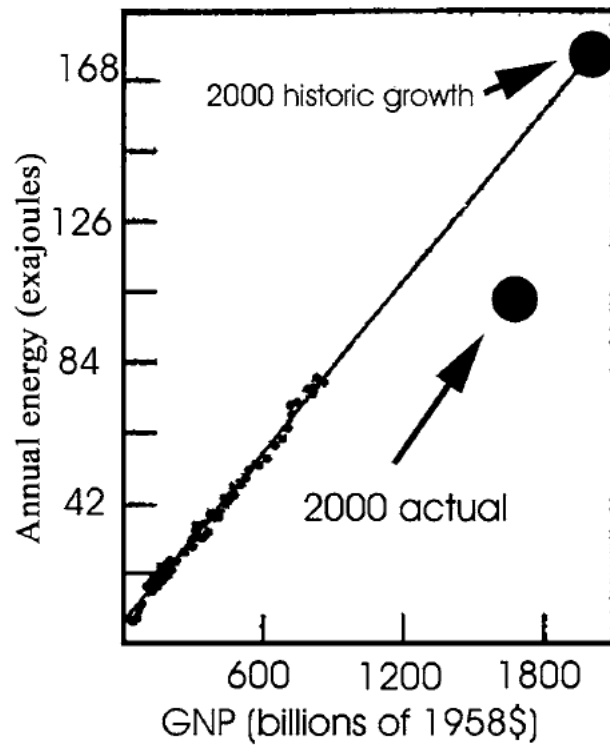
- (1) the median pathway (solid lines) and interquartile ranges (IQRs, grey shadings) of all scenarios (“n” denotes the number of scenarios);
- (2) the median pathway of scenarios constrained by cumulative BECCS, afforestation, and DACCS limits based on expert consensus of their future CDR potential⁴⁹ (“CDR-lim.”);
- (3) individual AR6 illustrative mitigation pathways: “IMP-LD” – strong emphasis on energy demand reductions; “IMP-Ren” – heavy reliance on renewables; “IMP-SP” – mitigation in the context of broader sustainable development; “IMP-Neg” – extensive CDR in the energy and the industry sectors; and “IMP-GS” – less rapid and gradual strengthening of near-term mitigation actions.

The projected levels of supply based on government plans and projections are shown by the black lines (“PGR21”), as estimated in the 2021 Production Gap Report

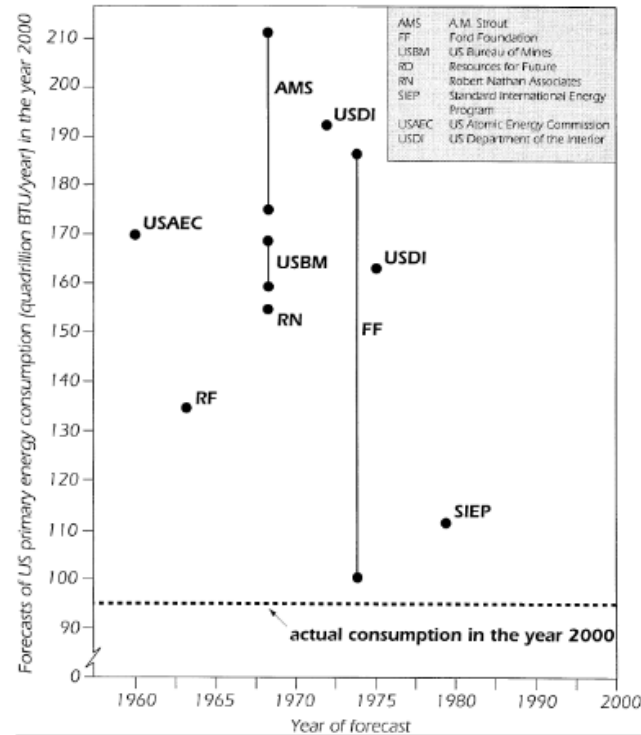
Conclusive remarks

Humility

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

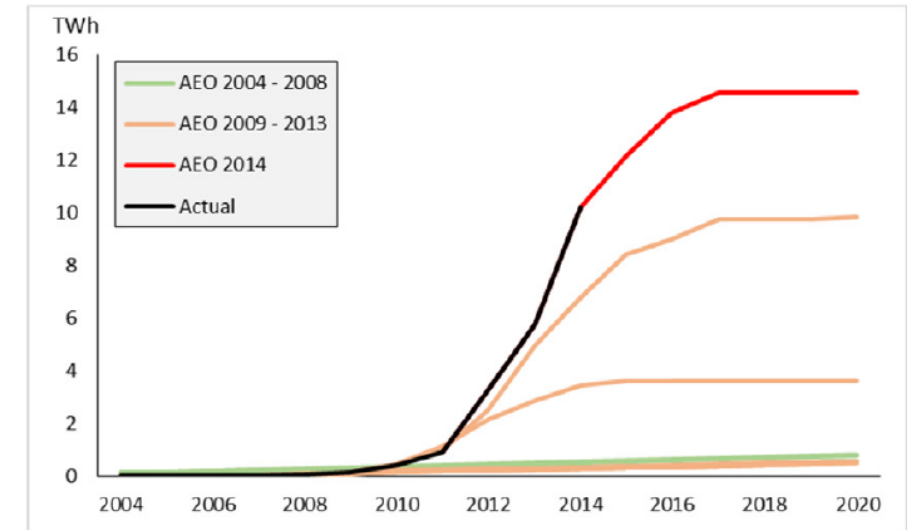


Craig et al. 2002. "What Can History Teach Us? A Retrospective Examination of Long-Term Energy Forecasts for the United States." *Annual Review of Energy and the Environment* 27 (1): 83–118.
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[https://doi.org/10.1016/S0040-1625\(99\)00097-9](https://doi.org/10.1016/S0040-1625(99)00097-9)

c. Solar PV (Electric Power Sector)



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

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Robust Decision Making and Scenario Discovery

