

Uncertainty Quantification in the Economy-Energy-Climate Chain

Tackling climate change requires making high-stakes decisions on the long-term evolution of economic, political, technological, energy, and climatic systems. The uncertainty of this complex system is profound and can lead to major mistakes if not taken at face value. Computational models have become central tools for systematically exploring possible futures and informing climate policy. However, these same models have grown exponentially in complexity and scale, relying on an increasing number of uncertain assumptions, while systematic approaches to understanding and communicating uncertainty have remained limited. This mismatch defines what we call the “uncertainty gap”.

In this thesis, we address the uncertainty gap through methodological advances in sensitivity analysis and use them to answer policy-relevant research questions using climate-economy and energy system models. In the first part, we build on recent sensitivity analysis approaches based on the mathematical framework of Optimal Transport, which are particularly suited for computationally expensive models with correlated inputs and multivariate outputs. We introduce the first software package for Optimal Transport-based sensitivity analysis, designed to facilitate the application of these methods to large-scale modeling workflows. We also develop a new family of sensitivity indices based on Sinkhorn divergence, substantially improving computational scalability and providing a bridge between existing sensitivity measures.

In the second part, we apply these methods to multiple classes of climate policy models, including integrated assessment models and capacity expansion models. Our applications include the analysis of future emissions pathways, the social cost of greenhouse gases, the European electricity transition, and the large-scale deployment of carbon dioxide removal technologies.

Applying methodological advancements to a variety of applications spanning the entire energy-economy-climate chain, we show how advanced uncertainty analysis can improve the transparency, robustness, and interpretability of climate policy assessments, helping quantitative models serve as tools for exploring alternative futures and supporting more robust decision-making.