Quantifying uncertainty in global and sub-global socioeconomic and greenhouse gas emissions futures

Steven Rose[a], Jennifer Morris[b], Angelo Gurgel[b*]

Abstract

Projections of future economic development, energy, emissions and climate involve a wide range of uncertainties. These projections often assume idealized policies. We employ a multi-sector coupled human-natural system model to explore both probabilistic parametric uncertainty and deep uncertainty about climate policy. Scenarios are used to capture deep uncertainties about policy design, including the level of policy stringency, the option for international emissions trading, the coverage of land use change emissions, and the availability of negative emissions technologies (e.g. bioenergy with carbon capture and storage, or BECCS). For each "optimistic" and "pessimistic" combination of policy design assumptions, we sample from probability distributions for model parameters such as total factor productivity growth, population, energy efficiency trends, costs of advanced technologies, fossil fuel resource availability, climate sensitivity, ocean heat uptake and aerosol forcing. We then assess the resulting uncertainty of key outcomes of interest at global and sub-global (regional, sectoral and technology) levels. This uncertainty characterization helps to inform policy discussions and decision-making. We show the impact of policy design assumptions on uncertainty in the distribution of emissions across regions, sectors and greenhouse gases, as well as energy and technology mixes and the cost of the policy. Several insights emerge, such as how failing to cover land use emissions can result in total emissions above the intended cap; how the availability of BECCS and credits for land use emissions can allow for a prolonged use of fossil energy; and how international emissions trading can benefit some regions more than others.

[a] Energy Systems and Climate Analysis Research, Electric Power Research Institute - EPRI
[b] Joint Program on the Science and Policy of Global Change, Massachusetts Institute of Technology - MIT
[*] Correspondence: gurgel@mit.edu

Introduction

Consideration of uncertainty in global socioeconomic and greenhouse gas emissions projections is needed for climate policy, planning, and risk management. This information is essential for, among other things, characterizing potential future climates, as well as impacts exposure and vulnerability, and mitigation strategies; informing global climate goals and their benefit and cost trade-offs; computing the social costs of carbon and other greenhouse gases; and assessing climate-related risks to economies and companies, as well as GHG goal setting.

Most socioeconomic and emissions projections to date, however, lack probabilistic interpretation or probabilistic coherency across variables and scales (spatial and temporal). This includes most global emissions scenarios/projections (e.g., RCPs, SSPs, IPCC databases), as well as national scenarios/projections, where there is no means for weighting the projections, or even a statistical interpretation of those scenarios (Rose and Scott, 2018, 2020). Furthermore, individual global emissions pathways are increasingly being prescribed to address climate change, or suggest national or company decarbonization strategies, without any consideration of whether there is sub-global uncertainty. Sub-global uncertainty is notable in ad hoc scenario results (e.g., IPCC databases), but understanding of the magnitude and shape of sub-global uncertainty associated with an individual global pathway is lacking.

In general, there is an absence of quantitative information and understanding regarding socioeconomic transformation uncertainty and risk relevant to international, federal, state, local and company decision-makers. Formal characterization of uncertainty about the future composition of society is needed and relevant to many climate and development decision-making applications.

Methods

To quantify uncertainty about future socioeconomic possibilities and structure, we develop a probabilistic multi-sector coupled human-natural system model and explore both parametric uncertainty and deep uncertainty about climate policy. Specifically, we expand the Economic Projection and Policy Analysis (EPPA) model (Chen et al., 2016) to a probabilistic global computable general equilibrium model (Morris et al., 2021a, 2021b), with economic production, consumption, and trade structure. Using the framework, we use Latin Hypercube sampling (n=400) from probability distributions for socioeconomic parameters to derive distributions for potential global and sub-global societies without and with additional climate policy, and with alternative decarbonization conditions. The uncertain socioeconomic input parameters include the following:

- Regional population growth
- Regional GDP growth (total factor productivity)
- Technology costs

- Elasticities of substitution (between capital and labor, between energy and other inputs)
- Energy efficiency trends
- Fossil fuel resource availability
- Urban pollutants initial inventory and trends
- Rate of technology penetration

We evaluate socioeconomic uncertainty for a range of global climate policy scenarios that limit global average warming to increasingly lower levels—Reference, Above 2˚C, 2˚C, Almost 2˚C, and 1.5˚C. For each global policy context, we also evaluate "optimistic" and "pessimistic" greenhouse gas (GHG) management conditions that represent deep uncertainties for climate strategy: international emissions cooperation, the availability of carbon dioxide removal technologies, and coverage of land use related emissions and carbon stocks. The optimistic condition is defined as one that includes global trading in GHG emissions permits, the availability of carbon dioxide (CDR) removal technologies, and global land-based GHG mitigation incentives. Conversely, the pessimistic condition does not include any of these mitigation mechanisms—international permit trading, CDR, or incentives for land based mitigation. Tables 1 and 2 provide a summary of the global policy pathways and the decarbonization conditions analyzed respectively.

Table 1. Global pathway definitions. Likelihood ranges for exceeding temperature levels represent the optimistic to pessimistic decarbonization conditions.

Global pathway	Description
Reference	No additional future climate policy (median 2100 temp 3.4˚C)
Above 2˚C	Peak 2.5˚C w/ 45-60% chance (< 3˚C 92-98%)
2˚C	Peak 2˚C w/ 58-60%, 2100 61-64% < 2˚C
Almost 1.5˚C	Peak 1.5˚C w/ 8-15% (< 2˚C 86-90%), 2100 25-33% < 1.5˚C (94-98% < 2˚C)
1.5˚C	Peak 1.5˚C w/ 21%, 2100 58% < 1.5˚C

Table 2. Decarbonization conditions

	CDR (BECCS & afforestation)	Land mitigation overall	International permit trading
Optimistic	Yes	Yes	Yes

Pessimistic	No	No	No

Each of the global policy pathways is implemented as increasingly stringent regional GHG emissions constraints, with Paris Agreement country pledges met by 2030 for G20 countries, and G20 country constraint stringency beyond 2030 defined by increasing rates of annual emissions reductions, and India and developing country GHG constraints defined by increasingly earlier emissions peaking years and increasing post-peaking rates of emissions reductions. The peak global average temperatures and likelihoods for the resulting global emissions pathways from the increasing regional emissions constraints were computed using the MIT Earth System Model (MESM) and are reported in Table 1.

Results

Figure 1 presents the mean and 98% confidence interval results for the reference socioeconomic conditions for a select set of variables globally and for the United States (US). In particular, we find that the fundamental non-policy parametric uncertainties regarding the characterization and dynamics of society imply significant future socioeconomic structural and emissions uncertainty globally and nationally. These uncertainties exist regardless of the climate policy and characterizing them on their own is a necessary first step to evaluating the implications for climate policy.

Figure 2 (left) presents the climate policy global GHG emissions trajectories relative to the reference condition range of emissions futures. Even the Above 2˚C policy represents a notable departure from the reference, with global emissions peaking by 2030 and declining. Note that the policy global emissions pathways are fixed by design via the regional emissions constraints. However, we do find some land related emissions leakage under the pessimistic conditions because land-based mitigation incentives are absent. The result is small global emissions ranges for the pessimistic policy design assumptions in Figure 2. Overall, the leakage is relatively modest and has a limited impact on the temperature outcomes (Table 1).

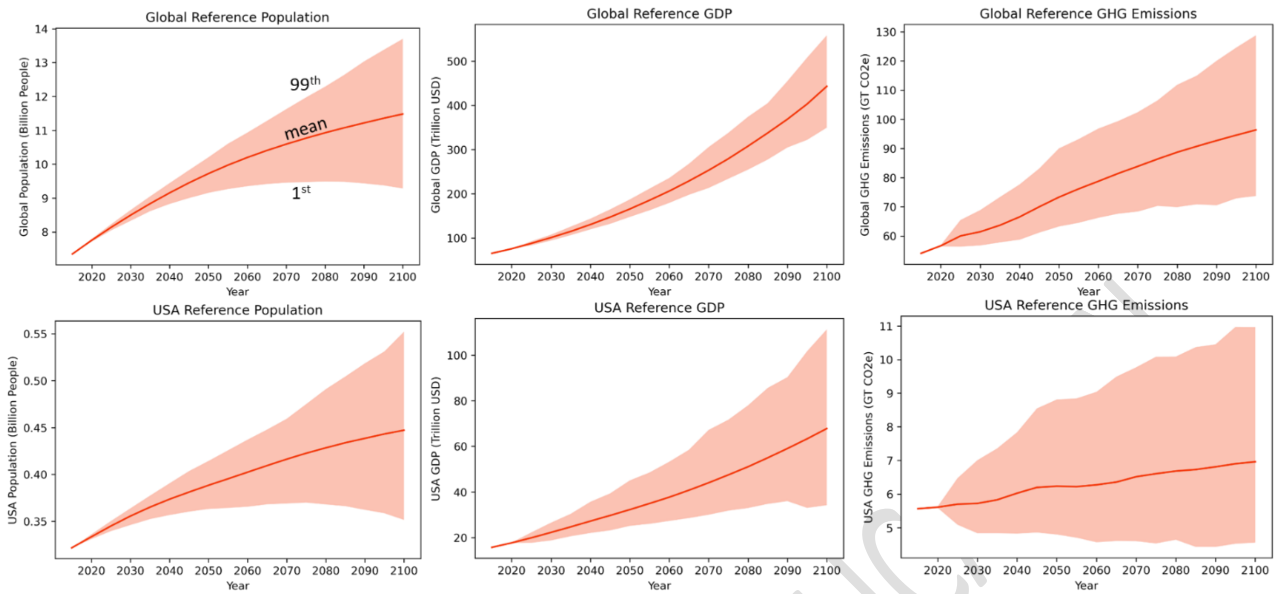

Figure 1. Reference global & US GDP, population, emissions uncertainty over time (mean and 1st to 99th percentiles)

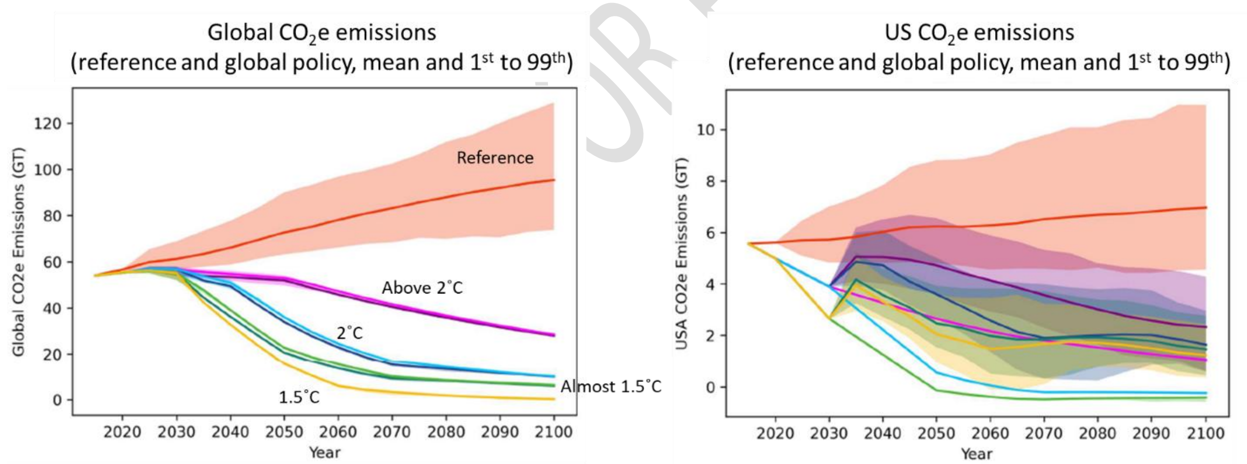

Figure 2. Global and US GHG emissions under alternative scenarios (mean and 1st to 99th percentiles). Darker/lighter shading indicates the optimistic/pessimistic mitigation conditions.

The right side of Figure 2 shows the corresponding US emissions pathway ranges for each global policy context. For a given global emissions pathway, we find a broad range of consistent US emissions pathways due to the socioeconomic structural uncertainties. The optimistic mitigation conditions are providing the US with significant emissions flexibility to manage the socioeconomic uncertainties and follow different cost-effective pathways depending on the socioeconomic circumstances. The pessimistic decarbonization conditions, on the other hand, do not offer the same flexibility and the US is forced to follow its respective regional emissions constraint.

Figure 3 illustrates the emissions situation confronting the US in 2050 for the 2˚C policy. The optimistic condition emissions distribution is wide, while the pessimistic condition distribution is narrow and essential a point. Both distributions, and the space between them, are relevant to decision-making. Given that the optimistic context of global cooperation with CDR and global land carbon incentives is somewhat unlikely, the pessimistic context results are equally relevant, if not more so. As a result, we find that the range of US emissions in 2050 consistent with a single 2˚C scenario extends from approximately 0.5 to 6 $GtCO_2e$/year.

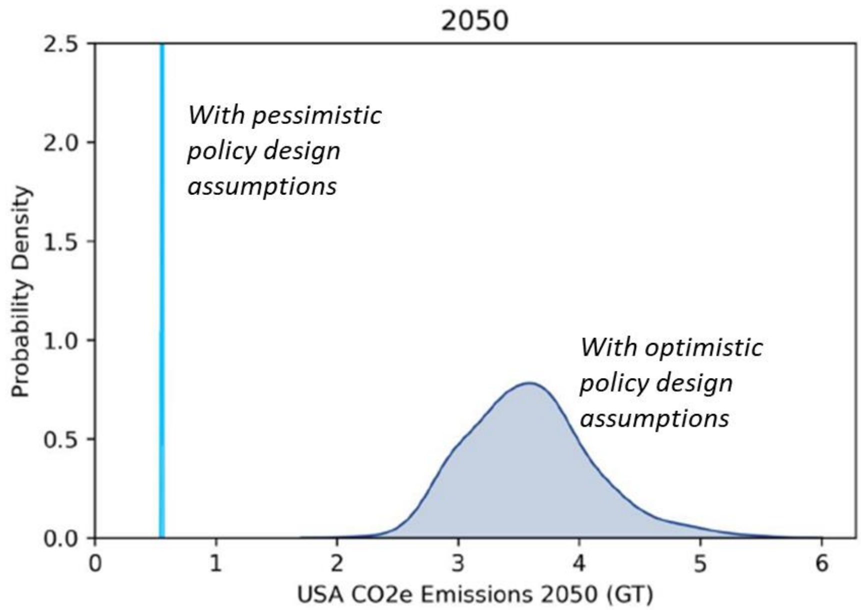

Figure 3. 2050 US emissions distributions for the 2˚C global policy scenario

We are particularly interested in uncertainty in the structure of the economy. Looking beyond emissions, we find significant US structural uncertainty for the 2˚C pathway in total energy, fossil energy, and electricity generation (Figure 4). The uncertainty distributions are broad for both the optimistic and pessimistic contexts, with the pessimistic distributions shifted to left and somewhat narrower due to the reduced flexibility for managing energy. Note that, despite the US emissions in the pessimistic context exhibiting no uncertainty in 2050 (Figure 3), there is still substantial uncertainty in the underlying 2050 economy; and, most importantly, both distributions of socioeconomic conditions—optimistic and pessimistic—are consistent with the 2˚C global pathway and relevant to decisions such as transition planning and risk assessment. We also, of course, find significant uncertainty in the relationship between variables (not shown), such as the energy and emission intensity of the economy, as well as in sectoral results, such as the size of sectors and production activities (e.g., technologies, inputs).

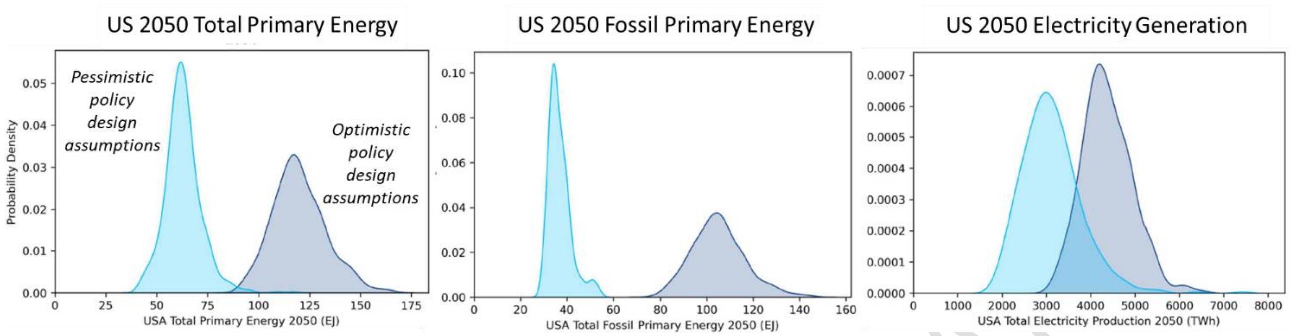

Figure 4. 2050 US distributions for the 2˚C scenario for total primary energy, fossil primary energy, and electricity generation

Looking across the global policies, we observe locational shifts in the distributions with lower global temperature ambition towards lower levels of emissions, energy, fossil energy, and electricity generation (Figure 5). However, we also confirm that, regardless of the global policy ambition, distributions of sub-global futures will be consistent with any global future, and across the optimistic and pessimistic distributions, the set of consistent societies is broad. Looking across policies in Figure 5 (top to bottom), we also find substantial overlap in results, suggesting that a single future can be consistent with multiple possible climate goals and outcomes, which is information relevant to hedging against uncertainty about the global future. Lastly, note that Figure 5 does not include any 1.5˚C pessimistic condition results. This is due to model infeasibilities. Regardless of the input parameter draw combination, we are not being able to find solutions for achieving 1.5˚C in the pessimistic context.

In addition to uncertainty in physical socioeconomic variables, like those related to energy, we are also interested in characterizing uncertainty in economic variables. Economic variables are unique in their ability to concisely capture the aggregate implications of the economy, including the aggregate implications of uncertainties throughout the global economy. Here we find that the optimistic conditions result in substantially narrower distributions for GDP and household consumption per capita losses associated with the global climate policies than under the pessimistic conditions. See Figure 6 for results for the US. The optimistic distributions of potential costs for the US shift towards higher costs and greater uncertainty as the global policy ambition increases, but the shifts are modest compared to the large shifts towards substantially higher costs and significantly greater uncertainty with the pessimistic conditions. For instance, with pessimistic conditions and the 2˚C policy, we find the possibility of greater than 10% losses per year in US household consumption per capita in 2050, and with the About 1.5˚C policy, the possibility of 25% losses per year. For 1.5˚C, we are not able to find any solutions, and the goal is out of reach.

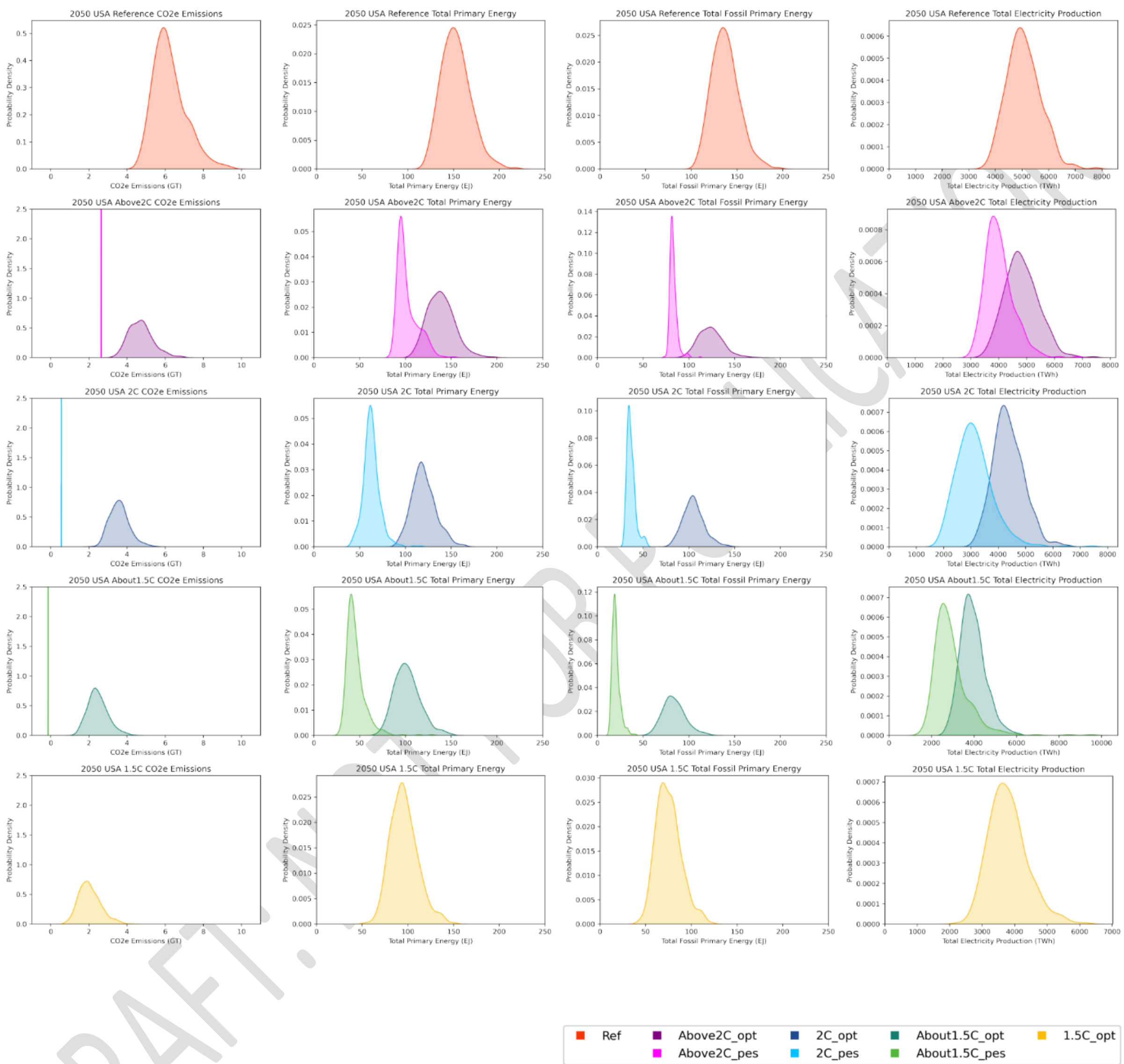

Figure 5. 2050 US optimistic and pessimistic distributions for reference (top row) and global policy scenarios (rows 2 through 5) for left-to-right: GHG emissions, total primary energy, fossil primary energy, and electricity generation. Note: 1.5˚C pessimistic scenarios could not solve. 1.5˚C electricity generation chart x-axis inconsistent with other generation charts.

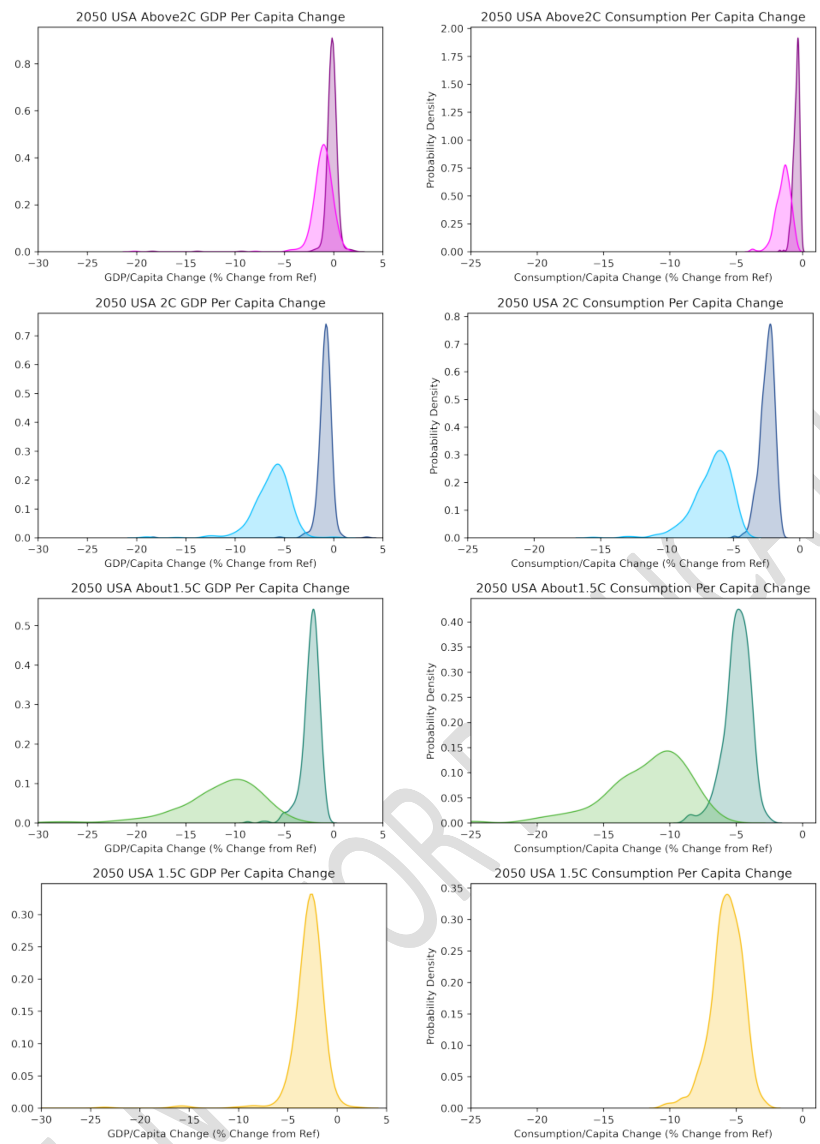

Figure 6. 2050 US optimistic (darker) and pessimistic (lighter) distributions of GDP and household consumption per capita costs with the global climate policies (% changes from reference). Note: 1.5˚C pessimistic scenarios could not solve.

Conclusion

We find uncertainty in socioeconomic structure to be significant, globally and nationally, as well as at the sector and household levels, with broad ranges of potential societies consistent with any global emissions pathway. The results suggest that uncertainty about the size of economies and their make-up is relevant and important to consider in climate risk assessment (transition and physical), social cost of greenhouse gas estimation, and GHG goal setting. Socioeconomic structural uncertainty will affect climate impacts, damages, and risks, by affecting societal exposure, vulnerability, and adaptation opportunities. It will affect potential country, sector, technology, and company transition roles and risks. It will affect country and company risk management strategies and practical GHG goals; and, it will affect discounting of the future when discount rates are modeled as consistent with economic growth.

Our results highlight that both climate policy *and* non-policy uncertainties are risks countries and companies need to consider and manage, and that planning for a single future (globally or sub-globally) is likely risky. A set of distributions—optimistic and pessimistic, as well as across policy stringency—is relevant to risk assessment and planning. Distribution overlap indicates that the same condition is consistent with different global futures and climates, which is useful information for risk management. In addition to informing risk assessments, our results could also be used to inform the weighting of development pathways in the literature.

Note that uncertainty about the attainability of global pathways themselves is also germane, especially given that our optimistic mitigation condition is an idealized upper bound, while our pessimistic condition is arguably more realistic, but in some ways still optimistic. As caveats, our analysis does not consider sectoral policy uncertainty. We assume economy-wide emissions reductions policies within each region, even in the pessimistic context. This type of policy assumption means that the least-cost mitigation *within each region* is chosen. Deviating from this assumption to sector specific emissions policies would not only likely result in an even greater range of relevant distributions, but also even higher potential regional mitigation costs than our pessimistic results. Also, although we explicitly model land use changes, we do not account for land-related uncertainties.

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