NBER WORKING PAPER SERIES

THE IPCC SHARED SOCIOECONOMIC PATHWAYS (SSPS): EXPLAINED, EVALUATED, REPLACED

Ivo Welch

Working Paper 32178
http://www.nber.org/papers/w32178

NATIONAL BUREAU OF ECONOMIC RESEARCH
1050 Massachusetts Avenue
Cambridge, MA 02138
March 2024

The IPCC Shared Socioeconomic Pathways (SSPs): Explained, Evaluated, Replaced
Ivo Welch
NBER Working Paper No. 32178
March 2024
JEL No. Q54,Q55,Q56

ABSTRACT

Shared socioeconomic pathways (SSPs) are perhaps the most influential economic policy analyses today. My paper evaluates their development, natural associations, logical consequences, and economic identification. All five SSP baseline scenarios are predicting scenarios that historical time-series analysis would consider empirically highly implausible. This alternative — econometric time-series analysis based on worldwide IPAT components — suggests alternative emission scenarios, mapping into expected radiative forcing of about RCP 6.5, with a reasonable plausibility range from RCP 4.5 to RCP 7.0.

Ivo Welch
Anderson School at UCLA (C519)
110 Westwood Place (951481)
Los Angeles, CA 90095-1482
and NBER
ivo.welch@anderson.ucla.edu

Climate change ranks among the top policy concerns in economics today. The definitive authority in the context of global warming projections is the *International Panel on Climate Change* (IPCC). Its Earth-science model (the coupled model intercomparison project [CMIP], an ensemble model) in the IPCC's Sixth Assessment Report (AR6) is based on *Shared Socioeconomic Pathways* (SSPs). These SSPs are essentially demographic, macroeconomic, and technological narratives. The SSPs are perhaps as central to the IPCC AR6 report today as the Earth Science climate models which directly build on them. Indeed, the AR6 describes the SSP aspects before it discusses the *representative concentration pathways* (RCPs, i.e., the analysis of global warming under different emissions), and usually discusses scenarios nearly always as SSP-RCP pairings.

The SSPs were developed by a large committee formed by participants of an environmental social science research community that spans many disciplines (climate scientists, sociologists, ecologists, energy engineers, civil engineers, hydrologists, etc.). Yet, as Noy (2023) points out, among those 15 identified economists in the AR6 report, none has ever published in a top-5 economics journal;[1] and fewer than half carry a work title of "economist." Thus, despite SSPs covering the same ground that many mainstream climate economists (beginning with William Nordhaus) have worked in, "mainstream" economists have by and large not been involved in the SSP design. They have not participated in or publicly critiqued the SSP scenarios. This absence of prominent climate economists in the design of what is perhaps the most consequential macroeconomic policy document in existence today seems startling.

However, the reverse is not the case. The SSPs are widely and increasingly cited and used in economic papers related to climate change (e.g., as in the prominent analysis of climate-based mortality in Carleton et al. (2022)). The importance of the SSP scenarios is also not limited to economic publications. The SSPs have been very influential also among other academics and among policymakers. Their citation counts far exceed those of any other economics paper of a similar vintage.

Therefore, my paper takes a first and belated step in examining these shared socioeconomic pathways from a mainstream economics approach and perspective. It argues that the SSPs should no longer remain unquestioned. It describes their conceptual

[1] The author informed me that this lack of publications also extends to disciplinary economic journals, such as *Environmental Economics*. This is however not the case for three authors from the larger community that authored the SSP final document adopted by the IPCC.

shortcomings, followed by a simple sensible alternative.

Part I: The Critique: Because many economists are not familiar with the SSPs, this paper begins with a brief description of how they were developed. Each SSP is described in a "narrative" (see the appendix) and preferentially paired with one particular "baseline" emission scenario. The key SSP paper (Riahi et al. (2017)) has more than 46 authors. Within their unified research development community, the separate SSPs can be viewed as compromises.

Aside from being scenarios of interest to the particular SSP social science research community, the SSPs are used in two primary ways explained in more detail below:

1. As inputs to the CMIP. In this context, the SSPs primarily provide pathways for *population* and *GDP per capita*. When augmented with (implicit) technology assumptions, each SSP-RCP pairing produces one emission pathway. The Earth Climate Working Group I then forecasts global warming on its *Representative Concentration Pathways* (RCPs). It is of central importance to the climate models that the emission scenarios span a wide range.

2. For the IPCC's stated reason:

   > ***Why do we need socio-economic scenarios?***
   > *The main purposes of socio-economic scenarios in the assessment of climate impacts, adaptation, and vulnerability are:*
   >
   > - *to characterise the demographic, socio-economic and technological driving forces underlying anthropogenic greenhouse gas emissions which cause climate change; ...*

   Yet, unlike the SSP development community, many policymakers do not begin with an interest in specific SSP scenarios and trace them forward to temperature scenarios. Instead, they are interested in global warming scenarios and want to trace them back to understand what causes them. Sometimes this is specific (e.g., "high emissions would come about due to across-country and within-country inequality"); sometimes this is more generic (e.g., "inequality, regional rivalry, fossil-fueled and sustainable development are the important determinants of global warming").

My paper will describe, analyze, and reevaluate the SSP compromises together with their baseline SSP-RCP pairings. The SSPs are perhaps the most important socioeconomic policy document in existence, so the economics profession cannot simply ignore them. Furthermore, mainstream economics papers are now increasingly building directly on the SSPs (and thereby also indirectly legitimizing them), a shaky foundation.

Importantly, my critique is *not* about the IPCC Earth science models (the CMIP), much less about the seriousness of global warming. Indeed, although I am not an expert on climate-change models, the CMIP appears to be based on sound science, theory, and empirical evidence. My concern is only with the nature of the deeper and easily replaceable IPCC's SSP emission scenarios. To the extent that the IPCC offers policy prescriptions on aggregate global emissions or adaptation, my paper does not suggest problems, errors, or mistakes.

Part II: The Alternatives: The SSPs can be replaced, because they are neither necessary nor sufficient. The second part of my paper offers empirical scenarios based on the three time series in the IPAT ("impact [is due to] people, affluence, technology") identity (Commoner (1972), Ehrlich and Holdren (1972)):

$$\textbf{IPAT:} \quad \text{Emissions} = \overbrace{\text{Population}}^{\text{demographic}} \times \underbrace{\overbrace{\left(\frac{\text{GDP}}{\text{Person}}\right)}^{\text{socioeconomic}} \times \overbrace{\left(\frac{\text{Emissions}}{\text{GDP}}\right)}^{\text{technological}}}_{\left(\frac{\text{Emissions}}{\text{Person}}\right)} , \tag{2}$$

The need for the integration of these three factors was also precisely the IPCC's stated motivation for offering socioeconomic scenarios in the first place — except that the SSPs failed to focus on them. The time-series model in my paper is not a novel approach: Similar paths were taken by Raftery, Zimmer, Frierson, Startz, and Liu (2017) (updated in Liu and Raftery (2021)), and Rennert et al. (2022), although they do not yet seem to have had much success in replacing the SSPs. The approach taken in my paper is perhaps even more simplistic — and yet, comfortingly, offers similar emission estimates.

The alternative socio-economic time-series process (TSP) models would *not* alter the concern about climate change. Indeed, the time-series analysis suggests that the

CMIP should consider scenarios in which (model input) emission quantities would associate with what will roughly *end up* with radiative forcing (model outputs) that are representative concentration pathways between RCP 4.5 and RCP 7.0, with RCP 6.5 as a good central estimate. (The RCP numbers are quoted based on central moments of anthropogenic emissions in exponential terms — akin to orders of magnitude.) This range here is defined roughly by the 1st percentile and 99th percentile of realizations in all three components of the IPAT identity, relative to historical trends:

- TSP "SSS" (likely about 3,000 $GtCO_2$ emissions by 2100 [about 40 $GtCO_2$/year], expected by the CMIP to result in about RCP 4.5): Population growth will be extremely low (1%), income growth will be extremely low (1%), and technological progress will be extremely fast (1%).

- TSP "MMM" (likely about 4,200 $GtCO_2$, RCP 6.5): Population growth will be roughly as expected by the United Nations, income growth will be roughly as it was over the last 1-2 centuries, and emissions-related technological progress will be roughly as fast as it has been in the past.

- TSP "BBB" (likely about 6,300 $GtCO_2$, RCP 7.0): Population growth will be extremely high (99%), income growth will be extremely high (99%), and technological progress will be extremely slow (99%).

Although fat-tail concerns suggest not considering these probabilities to be overly exact, *emission* scenarios below 3,000 $GtCO_2$ and above 6,300 $GtCO_2$ seem simply very unlikely. This does not necessarily apply to *radiative forcing* scenarios above RCP 7. Earth is not well enough understood to rule out such realizations.

Note that the IPCC has explicitly disavowed probability estimates, presumably based on a desire to avoid subjective disagreements about probabilities. This has led to the perplexing situation that the SSPs have now become subjective and difficult even to discuss. Put differently, on teleological grounds, a scenario with a prior 1-in-1-billion probability could be claimed to be as interesting as a most likely scenario with a 50% probability. Fortunately, the time-series projections from historical experiences make it possible to judge probabilities at least over the envelope. (Raftery et al. and Rennert et al. attempt more exact estimations of tail probabilities, a more ambitious approach than the one here.) With estimates for all three IPAT components, it is straightforward to assess that all five SSP scenarios are based on implausible paths. None of the five SSPs seem to entertain a plausible set of projections of population growth, income growth, and technology growth. It is not clear why empirically seemingly *implausible* scenarios are desirable inputs into the CMIP. Instead, socioeconomic scenarios could cover a very wide range of reasonably *plausible* outcomes. The possibility of active intervention could also justify adding some scenarios of lower emissions, because the SSPs are intended to be in the absence of intervention.[2]

Two final introductory comments are important. First, time-series analysis in terms of the necessary and sufficient ingredients would reduce the temptation to conduct incorrect back-inference, i.e., from overall warming scenarios to complex and unnecessary SSP narratives possibly unrelated to them. For example, a low-emission scenario could come about even in the absence of SSP1, a collective refocus on sustainability. It may also appear if there is more radical technological progress. Second, the time series modeling approach is an alternative to an integrated assessment model (e.g., Nordhaus and Boyer (2003)). The latter could also offer sensible scientific (empirically based) emission scenarios that the Earth Science CMIP could coordinate on (instead of on the SSPs). This is discussed further in Section IV.

[2]The lower SSP narratives seem to incorporate developments based on active intervention, contrary to the upfront statement of intent for the SSPs.

I Part I: The Shared Socioeconomic Pathways (SSPs)

A The IPCC Path to Its SSP-RCP Scenarios

The Earth physics model is developed by the IPCC Working Group I (Earth Science). It represents the core expertise of the IPCC, an organization originally founded by meteorologists and climate researchers. The "coupled model intercomparison project" (CMIP) is an ensemble model, capable of accepting a path of human emissions as input and producing a path of global warming as output. To a first approximation, the model maps higher total human emissions by 2100, to higher greenhouse gas atmospheric concentrations, to more radiative forcing (solar radiation), and thus to a higher global equilibrium temperature.

The CMIP outputs are called *Representative Concentration Pathways* (RCP) and are quoted on the basis of the output, with a value representing additional watts per square meter of solar radiation. RCPs are in exponential terms relative to emissions, with each unit increase in the RCP designation representing emissions that are about 40% higher. Thus, RCP 6.5 (an extra 6.5 W/m^2) represents total emissions of about 4,300 $GtCO_2$ (by 2100), while RCP 7.0 (an extra 7.0 W/m^2) represents about 5,200 $GtCO_2$.

The IPCC's social science research community (Working Group III) came into the picture because the Earth Science models are computationally extensive. The participants in the CMIP ensemble model wanted to coordinate on specific starting points of anthropogenic emissions, which the SSP-based emission paths provided. In effect, the social scientists have been directing the Earth scientists towards plausible emission scenarios that they should concern themselves with. In turn, many economic papers have followed the IPCC scenarios. For example, Carleton et al. (2022, p.2052) consider SSP2, SSP3, and SSP4, with outputs resulting in RCP 4.5 and RCP 8.5 scenarios.

The SSPs were passed onto Working Group I in Riahi et al. (2017), which concludes that "the pathways were developed over the last years as a joint community effort and describe plausible major global developments that together would lead in the future to different challenges for mitigation and adaptation to climate change... The SSPs are now ready for use by the climate change research community." The article has 46 authors and easily ranks among the most influential social science papers from 2017 (with 3,500 Google cites as of 2023). These SSPs are perhaps more apt to be characterized as "peer compromised" than "peer reviewed."

The socio-economic pathways (SSPs) with their narrative scenarios are now deeply integrated into the AR6 report. The AR6 naming scheme quotes SSPs even before RCPs, such as "SSP4-6.0," meaning "SSP Scenario 4 ("inequality"), leading to representative concentration pathway 6.0 W/m^2."

The IPCC report has prominently paired each SSP with one "baseline" emission (reference) scenario. These are recommended matches of SSPs and RCPs. For example, in the footnote of its very first figure (Figure SPM.1), the Executive Summary (IPCC et al. (1995)) states "Future projections (2021–2100) of changes in global surface temperature are shown for very low (SSP1-1.9), low (SSP1-2.6), intermediate (SSP2-4.5), high (SSP3-7.0), and very high (SSP5-8.5) GHG emissions scenarios." In the IPCC executive summary, this paired description occurs even before the first mention of RCPs. Similarly, the executive summary's very first table (Box SPM.1, Table 1) is dedicated to highlighting the specific pair associations of SSPs and RCPs. A reader with concern about inequality would thus likely first note that "inequality" is the title name of SSP4 and then note that inequality is associated with RCP 7.0. Conversely, a reader interested in "modestly above-average emission" scenarios would find that this scenario would be associated with inequality.

B The Original SSP Focus: Adaptation and Mitigation

To understand their current configuration, it is useful to trace the origins of the AR6 SSP scenarios. They began with Moss et al. (2010) and Kriegler et al. (2012) and were developed further by O'Neill et al. (2014). The original intent was to develop scenarios that would fit into a two-by-two matrix of adaptation challenges and conceptual mitigation challenges:[3]

		Adaptation Cost		
		Low	Mid	High
Mitigation Cost	High	SSP5		SSP3
	Mid		SSP2	
	Low	SSP1		SSP4

The variables on the two axes are conceptual. Indeed, although there are myriad *micro* (i.e., not worldwide but local context) studies, there are no widely used empirical proxy measures for *worldwide macro* adaptation and mitigation costs or challenges. The absence of clearly articulated empirical proxies for worldwide adaptation and mitigation costs renders further SSP analyses more difficult to assess, to look back at history at the roles of adaptation and mitigation in emissions, and to potentially reject or replace them. However, it is also not unusual for economists to begin with broad theoretical constructs before measuring them with empirical proxies.

This reliance on measures not readily available contrasts with integrated assessment models (IAMs) — e.g., the evolving DICE model of climate change by William Nordhaus of Yale (Nordhaus (1992)) — which are built intentionally around more measurable inputs or (calibratable) outputs, such as population growth and GDP growth.

[3] I will abbreviate "challenges" as "costs," a more easily measured attribute often used in economics.

C Change of Focus: More Complex Narrative Scenarios

The next step in today's SSP bases was the augmentation of the adaptation-mitigation matrix with other socioeconomic forces. The selection was not empirical (e.g., by cluster analysis from historical proxies of economic, political, or sociological forces), but rather based on the interests of participating environmental social scientists. The resulting "narratives" were ultimately grouped and chosen by committees of participating social and other scientists.

The narratives are quite elaborate. The appendix reproduces the headline characterizations. They describe roles for security issues, nationalism, faith in competitive markets, effective management of ecological systems and geoengineering, the materiality of consumption, environmental degradation, inequality both across and within countries, sustainability, human capital and investment, knowledge- and capital intensity, diversification of a globally connected energy sector, environmental policies, market integration, and others. I note that in addition to the difficulty of empirically measuring each and all of these concepts globally, economists have in the past shown little confidence in their abilities to model and predict these complex and myriad forces on the long-term decade-long and worldwide bases here called for. Appendix $\mathcal{B}$ illustrates how narrative vagueness and ambiguities can lead readers to different understandings.

As mentioned, the SSPs are themselves defined to be viewed as *in the absence of* climate policies. Yet, some of the mentioned forces in the narratives seem exogenous to climate policy, while others seem to be inputs into or outputs of environmental policies. It is rarely clear what aspects are causal drivers and what are merely correlates. It is simply difficult to tell and no further clarification can be obtained from the IPCC. A reader could easily confuse the two and incorrectly attribute causality where the authors only meant correlation — or vice versa.

The SSP socioeconomic models contrast sharply with the climate-science RCP models, which are empirically-calibrated models with clear distinctions between exogenous and endogenous components.

Following the original adaptation-mitigation matrix, based on these narratives, the SSP research community then augmented its matrix to cover five narratives and attributed them to the matrix cells, as follows:

		Adaptation Cost		
		Low	Mid	High
Mitigation Cost	High	SSP5 Fossil-Fueled		SSP3 Regional Rivalry
	Mid		SSP2 Middle of the Road	
	Low	SSP1 Sustainability		SSP4 Inequality

The *particular* associations of mitigation and adaptation costs with narrative scenarios seem neither necessary nor sufficient. Technological development would seem highly important, but they are not primary aspects of the narratives.

Some of the scenario arrangements seem outright illogical. For example, why would high adaptation costs and low mitigation costs be characterized by inequality and vice versa? It is not difficult to imagine that the world could have high inequality with low adaptation costs or high mitigation costs; or one in which there are high adaptation costs and low mitigation costs and yet less inequality. It is only “high mitigation costs” that would seem to logically associate with high fossil-fuel development.

D Measures of Population and GDP Growth

The five narratives were then augmented by Dellink, Chateau, Lanzi, and Magné (2017) with population ("Pop") and GDP forecasts. These two assigned variables gave specific (and, by their official IPCC adoption, now necessary) meanings to the manifold aspects of SSPs. Specifically, for 2100, the scenario forecasts are as follows:

Mitigation Cost \ Adaptation Cost	Low	Mid	High
High	SSP5 Fossil-Fueled Pop: 7b. GDP/Pop: $139k		SSP3 Regional Rivalry Pop: 13b. GDP/Pop: $21k
Mid		SSP2 Middle of the Road Pop: 9b. GDP/Pop: $60k	
Low	SSP1 Sustainability Pop: 7b. GDP/Pop: $13k		SSP4 Inequality Pop: 9b. GDP/Pop: $38k

From a social scientist's perspective, measurability is commendable. Having population and GDP measures gives at least some specific empirical meanings to these five SSP scenarios.[4]

However, and again, these pairings seem neither necessary nor sufficient and at times illogical and/or implausible in magnitude. For example, it does not seem necessary that "inequality" *would* be associated with higher population growth than either sustainability or fossil-fueled development. Of course, it is also not impossible that inequality *could* be associated with higher population growth than either sustainability or fossil-fueled development. I am not aware of empirical research that supports or rejects these essentially macroeconomic and macro-demographic associations (Galor (2011), Spolaore and Wacziarg (2022)).

[4] The forecasts themselves relied on competent economic modeling of GDP, population, and other variables. The scenarios also allowed for many degrees of freedom, making it possible to fit them suitably into this SSP matrix. The author has informed me to expect an update soon, which will lower short-term expected living standard growth, though not necessarily long-term expected living standard growth.

E Baseline Pairings For Scenario Linkages

Given population and GDP predictions, the socio-economic scenarios were handed over to the Earth science modeling community. Working Group I now considered a full complement of possible RCPs, with population and GDP fixed by each individual SSP scenario.

However, after the CMIP predicted warming based on assigned RCPs and emissions (as input by each SSP), there were still too many scenarios to make understanding and reading the IPCC report easy. Thus, the IPCC preferentially paired specific SSPs with specific RCPs and focused its report primarily on these pairs. They have become the central focal points for the discussion of climate change:[5]

Mitigation Cost \ Adaptation Cost	Low	Mid	High
High	SSP5 Fossil-Fueled Pop: 7b. GDP/Pop: \$139k Baseline: RCP 8.5		SSP3 Regional Rivalry Pop: 13b. GDP/Pop: \$21k Baseline: RCP –
Mid		SSP2 Middle of the Road Pop: 9b. GDP/Pop: \$60k Baseline: RCP 4.5	
Low	SSP1 Sustainability Pop: 7b. GDP/Pop: \$13k Baseline: RCP 2.6		SSP4 Inequality Pop: 9b. GDP/Pop: \$38k Baseline: RCP 7.0

Again, these pairings also seem neither necessary nor sufficient. For example, “easy to mitigate, difficult to adapt” (SSP4) would seem to be a more suitable candidate to be associated with very low emissions (RCP 2.6). Instead, SSP1 (“easy to mitigate, easy to adapt”) was chosen to associate with RCP 2.6. It is not clear (and perhaps illogical) why the world would be on a lower emission trajectory if adaptation costs were low.

[5]The SSP database is still describing baseline emission scenarios from AR5. These have changed in AR6. Unfortunately, the SSP database, https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=10, with suggested citation of Riahi et al. (2017), has not been updated.

Reorganizing the IPCC table suggests the following baseline linkages:

RCP to SSP in IPCC AR6, Year 2100 Forecast

RCP	Emissions	Baseline	Population	Living Standard	Narrative
2.6	Low	SSP1	7 billion	$13k/year	Sustainability
4.5	Low Medium	SSP2	9 billion	$60k/year	Middle of the Road
6.0	High Medium	SSP4	9 billion	$38k/year	Inequality
8.5	High	SSP5	7 billion	$139k/year	Fossil-Fuels

In sum, the pairings seem subjective and at times not even logically necessary or consistent. But perhaps most importantly from a policymaking perspective, it is tempting but surely incorrect to work backward, from a global-warming scenario to a socio-economic scenario. The SSPs may be argued by their community to be sufficient in leading to particular forcing (though the scenarios have not been clear enough to assess this), but there should be no arguing that they are necessary. For example, low emissions could come about in the absence of all sustainability arguments in the SSP1 description if technological change were to experience revolutionary breakthroughs.

I will return to the logic and plausibility of these pairings in Section IV.

F Issues and Improvements

The IPCC SSP scenarios are not an economic theory, in which a clear set of assumptions leads to a clear set of the asserted causal and logical associations. Indeed, as mentioned above, many statements in the narratives appear to be neither necessary nor sufficient. It is easy to come up with counterexamples that break the chain of logical reasoning. Without a logical theory, it is difficult to bring empirical data to bear on deciding its validity. In particular, it does not appear that the SSPs claimed forces could be empirically tested on the macro-based world data to which they pertain. This is because the SSPs have not only no clear identification of what forces are endogenous or exogenous, but also that the narratives are also so vague that it is not even clear what measurable variables should be involved. From a time-series perspective, the narratives are also implausible in the constellation of outcome variables (GDP, population, and emissions) that they project.

There is a lack of engagement by economists in the IPCC Working Group III that concerns itself with the SSPs (itself strongly overlapping with the SSP design community). Noy (2023) describes in the journal *npj-climate action (Nature)* that "The selection process of IPCC authors is in most cases very opaque, and the selection process that predates it at the national level is even more obscured. This selection is an inherently political process..." Recognizing the problem, Hsiang and Kopp (2018) called for more engagement (but did not directly critique the SSPs):

> However, many economists with expertise that would be useful to these modeling exercises have remained unengaged with (or unaware of) this enterprise. In our view, deepening engagements with economists in subfields outside of energy economics, such as macroeconomics, development economics, and political economy, will help strengthen and accelerate this research program...

Informal conversations with prominent climate economists who have tried to engage with the SSP research community suggest that they were not welcome.

My paper disagrees with Hsiang and Kopp *in this SSP context*. The reason why it is difficult for economists to engage is the difference in approach. The gulf between a positive economic approach (Friedman (1953)) and the SSP narrative approach is simply too wide. This makes the socioeconomic IPCC Working Group III (and the journals in which the SSPs are developed) difficult for economists to engage with. To make the SSPs meaningful to economists would require improving the narratives in at least four ways:

1. Evidence in how the individual components in an SSP narrative naturally cluster together to warrant being included in the same one.
2. Specificity in how each individual component in an SSP narrative is necessary to cause the GDP and population dynamics that are associated with them.
3. Clarity in what variables are exogenous and endogenous.
4. Guidance in how the variables can be empirically measured on the macro level on which they are intended to work.

Such improved SSPs would still not define the sufficient conditions for GDP, population, and (with RCPs) technology assumptions, but they would provide a logical, empirically-testable economic theory.

II Part II: Simple Time-Series Process Alternative

Instead of the deep SSP scenarios that rely on numerous narrative assumptions, similar to Raftery, Zimmer, Frierson, Startz, and Liu (2017) and Rennert et al. (2022), I now sketch and contrast a (more) parsimonious alternative on which the CMIP could be coordinated on. The method is time-series empirical analysis of the historical IPAT emission components, based *exactly* on the IPCC's stated objective to "characterize the demographic, socio-economic and technological driving forces underlying anthropogenic greenhouse gas emissions which cause climate change" — no more, no less. The aforementioned IPAT equation is

$$\textbf{IPAT:} \qquad \text{Emissions} \;=\; \text{Population} \times \left(\frac{\text{GDP}}{\text{Person}}\right) \times \left(\frac{\text{Emissions}}{\text{GDP}}\right) ,$$

The identity guarantees that its component driving forces are both necessary and sufficient.

The time-series alternative is objective, empirical, replicable, and easily updatable. Its emission forecasts can span similar emission ranges as the SSPs. Moreover, unlike the SSPs, they are also consistent both with expert technology forecasts (such as those from the EIA) and integrated assessment models (such as those from DICE).

For the population component, my approach adopts existing prominent expert forecasts, primarily those of the United Nations. My time-series process (TSP) approach proposed here further assumes that the historical processes driving the evolution of the ratio components (the driving forces in IPCC parlance) are stable. In this case, their empirical histories can be analyzed using standard econometric tools. My TSP analysis thus fits the above ratios on historical data from the highly respected U.S. Energy Information Agency (EIA) from 1990 to 2020. The resulting scenario forecast ranges are then based on TSP-defined extrapolations into the future.

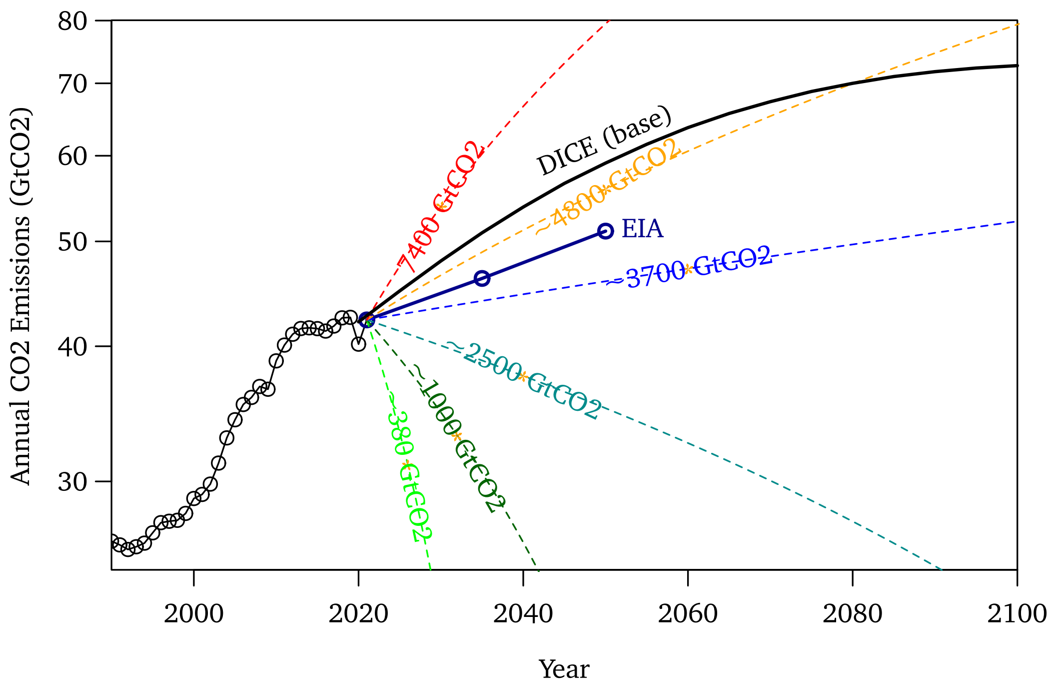
Equation (1) has the advantage that it makes it easy to integrate priors about living standards and impending clean-energy-technology-based emission reductions. Equation (1) seems even more promising predictively, because worldwide emissions per person have been very stable for many decades now. They are also further predicted by the EIA —a relevant expert body — to increase only very slowly for another three decades (see Figure 3). Projecting another five decades of stable or only slowly growing emissions per person beyond the first 30 years of energy-informed EIA forecasts thus seems a reasonable leap of faith, as of today (2023), even in the presence of strong continuing increasing living standards and clean emissions technology.

A Other Global Emission Path Scenarios

fig:co2 in rcpssp.tex, February 26, 2024

The goal of the TSPs is to outline a range of emission scenario pathways that the CMIP should consider and coordinate on. Other models have already provided such projections.

Figure 1: Total Annual Emissions (CO_2) Under 2021-2100 Scenarios



Explanations: Emissions are truncated at zero for low emissions scenarios. Thus, the 300 $GtCO_2$ and 1,000 $GtCO_2$ emission scenarios end up at zero emissions by 2100. The numbers on the rays show the sum of all CO_2 emissions 2021-2100. The Nordhaus "DICE (base)" model (in the absence of intervention) is marked in Black.

Figure 1 illustrates a few arbitrary but simple linear monotonic paths of CO_2 emissions (on a log scale) of about 1,000 $GtCO_2$ (roughly SSP1-26), 2,500 (SSP2-45), 3,700

(RCP 6), 4,800 (RCP 7), and 7,400 $GtCO_2$ (SSP5-85). To emit only 1,000 $GtCO_2$ would require zero emissions in about 50 years (with reductions of about 0.8 $GtCO_2$ per year). The other emission pathways end in 2100 with final-year emissions of about 22 $GtCO_2$ (and reductions of 0.2 $GtCO_2$ per year), 52 $GtCO_2$, 79 GtCO2, and 145 $GtCO_2$, respectively.

The plot also shows two other predictions. The first is from the EIA. If extrapolated, its slope would suggest cumulative emissions by 2100 of about 4,500 $GtCO_2$ (roughly RCP 6.2), causing radiative forcing of about 6.5 W/m^2. The second is the DICE model zero-intervention case. It suggests a concave function but ends with roughly the same cumulative emissions in 2100 as the EIA projection.

Note that the final year 2100 is not magic. If the path is convex, emissions to 2100 (and thus global temperature) will be lower than under constant change — but post-2100 emissions would then be higher than under constant change. If the emission path is concave, emissions to 2100 will be higher, but post-2100 emissions will then be lower.

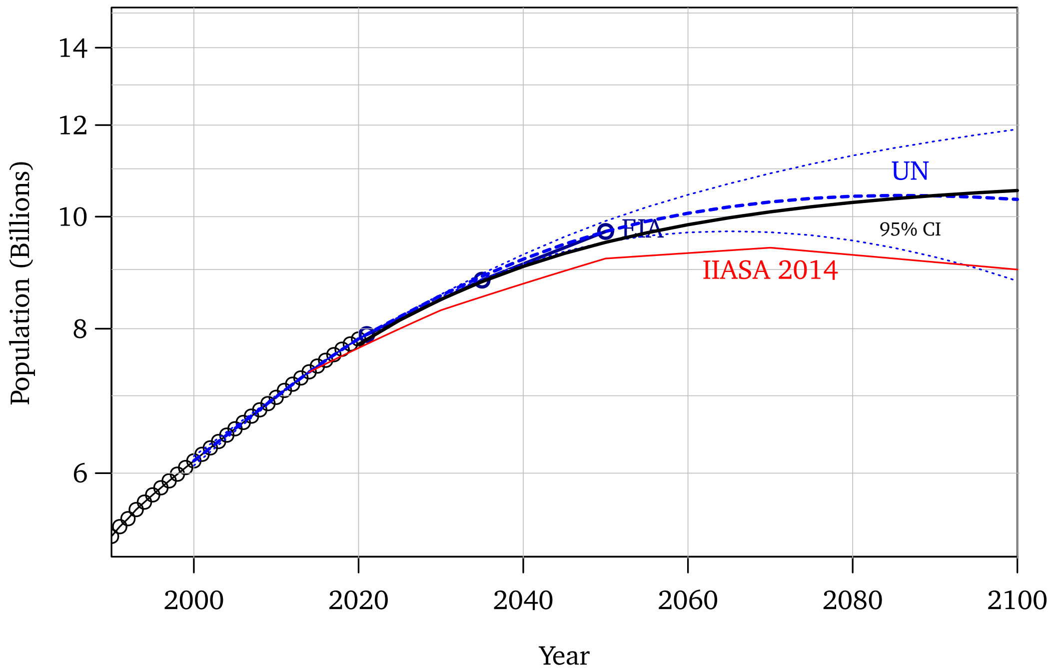
B Population

Demographers predict a mean-reverting world population this century, based on research into demographic transitions, human lifespans as long as 80 years, and long-standing concave growth patterns.

The United Nations and the International Institute for Applied Systems Analysis (IIASA, see Lutz, Butz, and Samir (2017)) are already specialized experts in predicting future demographics. Their forecasts are themselves based on disaggregated country-based empirical analyses. Thus, there is no good rationale for me to attempt to improve on their predictions. It seems wisest to adopt their forecasts.

Figure 2 plots these population forecasts. The United Nations forecasts offer confidence bands that IIASA does not. It seems reasonable to attribute similar proportional uncertainty to the (now modestly dated) IIASA forecasts as to the (more recent) United Nations forecast — roughly a 15% band by 2100, suggesting a IIASA 95% range of 7.7 to 10.4 billion. Like many other forecasters, the EIA has largely adopted the UN model. The DICE statistical population model (black line) also largely follows the predicted UN

Figure 2: Population Forecasts



Explanations: Data Sources: United Nations (2020) and IIASA (2014). The EIA, UN, and (untitled black) DICE base model population forecasts are nearly identical. The IIASA model predicts lower population growth.

population growth until about 2100. My TSP will adopt 8 billion as a low scenario and 12.7 billion as a high scenario.

C Time-Series Statistical Models of Ratios

The other IPAT components are the ratios that need to be forecasted: either the CO_2/Pop ratio, or its two components GDP/Pop and CO_2/GDP.

Despite or because of more than a century of research in economics, most economists believe that they have little ability to predict unusual changes in worldwide GDP growth over the coming 80 years. Average *worldwide* economic growth rates have tended to move (perhaps decline) only very slowly. Furthermore, if the relevant domain experts at the EIA are to be believed, the same seems to be true for technological emission-reduction progress and implementations. (In recent decades, both worldwide GDP growth and clean technology have improved again, after earlier decades of smaller gains.)

My TSP projections rely on historical data from the EIA, beginning in 1981 and ending in 2021.[6] Such TSP analysis suggests that log changes of these ratios are following random walks with constant drift and variance:

$$\log(\text{Ratio}_t) = \log(\text{Ratio}_{t-1}) + \mu + \epsilon_t \qquad \epsilon_t \sim N(0,\sigma) \tag{3}$$

A log-change specification is empirically justified because all three ratios are extremely persistent. The estimation is best performed in (log) changes.[7]

$$\log(\text{Ratio}_t) - \log(\text{Ratio}_{t-1}) = \mu + \epsilon_t \qquad \epsilon_t \sim N(0,\sigma) \tag{4}$$

I conducted but am not reporting diagnostics that include an investigation into heteroskedasticity and into the role of lagged terms of its own and other ratios (as well population changes). A vector-autoregression does not seem to improve prediction. Appendix B briefly describes the contemporaneous correlation structure, useful in assessing range confidence.

An advantage of the TSP analysis is that it offers a quantitative indication of its own forecasting uncertainty. This makes it possible to select a desired confidence range for scenarios. For example, we can consider predicted 1-in-200 (0.5%) outcomes to be on the extreme side. However, these extreme quantitative estimation uncertainties are based on a probable over-optimistic assessment of process stability and do not incorporate a (Bayesian) penalty function. The estimates are indicative, not definitive.

If a variable follows a stable random-walk process, its long-term mean grows linearly in the number of years ($T \cdot \mu$) while the long-term standard deviation grows with the square root ($\sqrt{T} \cdot \sigma$) . This makes it easy to calculate 95% and 99% confidence intervals under the additional assumption of iid Gaussian normal distributions of ϵ_t.

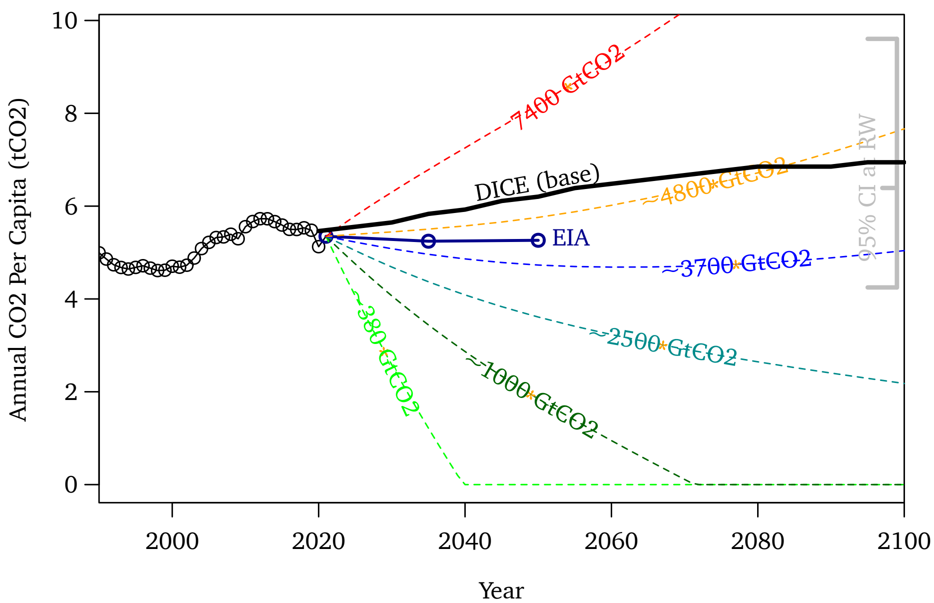
[6]EIA numbers have been scaled by a factor of 1.193 to reflect that their CO_2 forecasts are fossil-fueled CO_2 emissions only. The IPCC works with forecasts of CO_2 from all sources. The estimates used here also ignore all non-CO_2 emissions. Thus, one may scale up other greenhouse gases or model them analogously.

[7]The single-year mean (sd) of the annual log change series is 0.002 (0.023) for $\log(CO_2/\text{Pop})$, starting from $\exp(1.677) \approx 5.35$ in 2021; 0.019 (0.172) for $\log(\text{GDP}/\text{Pop})$, starting from $\exp(2.813) \approx 16.66$; and –0.0165 (0.013) for $\log(CO_2/\text{GDP})$, starting from $\exp(-1.136) \approx 0.3212$.

C.1 Emissions Per Person

Figure 3 shows that emissions per person have remained stable for decades (at 5.0 tCO_2/person/-year in 1990, increasing to 5.1 tCO_2/person/year in 2020).

Figure 3: Emissions Per Person Forecasts



Explanations: Data are from the EIA for emission and from IIASA for population. Projections use yearly population forecasts ending in 7.6 (IIASA low 95%), 10.35 (UN mid), and 11.9 billion people (UN high 95%), respectively. The EIA model predicts lower per-capita emissions than the DICE (base) model, which itself predicts roughly what the [M][M][M] time-series model will predict (see confidence interval [CI] on the right).

Modeling the time-series process for CO_2-emissions per person as a random walk with drift, as in eq. (3), forecasts year-2100 mean estimates and confidence intervals (CI) of

	2100est	95% CI	99% CI	99.9% CI	
CO_2/Pop	6.4	4.2 to 9.6	3.9 to 10.4	3.2 to 12.7	in tCO_2/person/year

The upper 99% extreme-scenario global emissions (10.4 tCO_2/person/year) is significantly larger than even today's OECD emissions (though below today's U.S. emissions). In the context of improving clean technology and efficiency, such a high projection seems appropriate for a still plausible yet extremely unlikely 0.5% probability "high-emissions scenario." The lower extreme of 3.9 tCO_2 is roughly equivalent to today's per-capita emissions of poor countries like North Korea, Cuba, and Mexico, as well as Sweden, a country already blessed with an abundance of clean hydro-energy today. (The uncertainty is also graphed on the right margin of Figure 3). Not shown, standard diagnostics suggest that $\log(CO_2/Pop)$ fits the assumption of a random walk quite well. Its log changes have almost no autocorrelation or heteroskedasticity.

Figure 3 also shows that the forecasts of the EIA, the no-intervention DICE, and the TSP models are largely in agreement. The EIA forecasts 5.3 tCO_2/person/year for 2050, based on its disaggregated country, technology, and energy analysis. The no-intervention DICE model forecasts about 6.0 tCO_2/person/year for 2100. The DICE forecast is just modestly (less than one standard deviation) lower than the TSP model forecast of 6.4 tCO_2.

Note also that it follows that emissions stability per person means that much of the growth and decline in future worldwide emissions will be driven primarily by the growth and decline of the world population.

C.2 Decomposed Emissions Per GDP and GDP Per Capita

Instead of modeling emissions per person, one can model its two components, CO_2 per GDP and GDP per capita. This yields the following predictions:

	EIA (scaled)			Random Walk with Drift (eq. 3)		
	1990	2020	2050est	2100est	95% CI	99% CI
CO_2/Pop Components:						
GDP/Pop, in $k/year	9.3	15.8	28.4	74.8	55.2 to 101.1	52.2 to 107.0
CO_2/GDP, in g/$	0.53	0.32	0.18	0.09	0.068 to 0.112	0.065 to 0.112
CO_2/Pop, in tCO_2/year	5.0	5.1	5.3	6.4	4.2 to 9.6	3.9 to 10.4

(The last line repeats the product, as in emissions per person per year.) The decomposed historical TSPs thus suggest the following:

GDP/Capita: Historically, log(GDP/Pop) has fit a random walk with a strong positive drift quite well. The statistical forecast suggests a per-capita GDP growth to 2100 of about 2% per year ($75k/year), with a 99% confidence interval from 1.5% ($52.2k/year) to 2.4% ($107k/year). This is in line with forecasts of professional agencies today.

Note that these estimates ignore *worsening* feedback effects, in which higher income growth feeds back into more emissions, which feeds back into lower income growth. This would suggest not being as concerned about extreme income growth scenarios. However, not much more can be said. The historical data does not indicate the presence of such a strong link *yet*. Involved feedback loops are the domain of integrated assessment models (IAMs), not those of simple TSPs.

It is possible (but not clear) that disaggregated country-based analyses could improve the quality of the prediction of worldwide per-capita growth aggregates (Henderson, Storeygard, and Weil (2012)). However, it seems unlikely — given the limited understanding of today's economics — that better forecasts today would greatly expand the plausible TSP-series scenario range from 1.5% (95% CI) to 2.4% (99% CI). These two growth rate ranges already seem rather stark — and enough to worry about. More involved GDP forecasts are also unlikely to offer U-shaped economic growth, one way or another.

CO_2/GDP: As technology has progressed and developing nations have leapfrogged over older more pollutive and less efficient technologies (e.g., adopted better insulation and other improvements as they have become wealthier), there has been a steady improvement in the efficiency of worldwide technology (CO_2/GDP).

From 1990 to 2020, EIA's history describes an emission reduction of about 40%. The EIA projects reaching 0.18 g/$ by 2050. **Perhaps surprisingly, from 2020 to 2050, the EIA projects only a modest acceleration of the rate of decline in pollutiveness to 43% from the historic 40%**, despite stark advances in clean-energy technology. If this decline continues at the same rate to 2100, emissions could fall to 0.07 g/$.

The random-walk model is based on history only and is unaware of impending (3% additional) improvement in clean technology. Of course, it also projects much higher emissions efficiency by 2100, though perhaps not *as* high. It expects 0.08 g/$.

It is perhaps here — in the context of emissive technology — that the forecast could better be based less on historical data analysis and more on conceptual forecasts, taking into account the projection of rapid clean energy progress. Some energy experts may suggest further reducing the lower extreme 1% bound of 0.065 which the TSP suggests.

Statistically, unlike the other two series (emissions per person and living standards), changes in log(CO_2/GDP) still have mild positive autocorrelation. This would suggest widening the log(CO_2/GDP) scenario range.

C.3 Comparison of Emissions Per Person vs. Component Forecasts

The TSP analysis in this paper is simplistic. It is possible to model more involved time-series processes, and even integrate other variables. The estimation sophistication reflects the length constraint of this paper. However, it seems unlikely that more sophisticated processes would suggest greatly different bounds or pathways.

Forecasting CO_2/Pop had the advantage that its value has held fairly steady, in contrast to the large negative drifts (CO_2 emissions per dollar of GDP) and positive drifts (GDP per capita), respectively. It also avoids having to forecast the covariance between CO_2/GDP and GDP/Pop. And diagnostics suggest that its time-series process has been statistically very well-behaved for many decades.

Forecasting the components had two advantages. First, GDP per capita is a process that has been well studied by economists and the process has been empirically assessed to be close to a random walk (e.g., Cochrane (1988)). Second, it makes it easier to incorporate conceptual insights about the technology ratio, i.e., emissions per dollar of GDP. For example, one can assume an accelerating decline of CO_2/GDP as renewable energy seems to be improving faster than it has in the past. Clean energy technology could indeed disrupt the historical trend of pollutiveness and thereby break the association between the two components of CO_2/Pop.

However, before one gives in to the temptation to do so, one should have acquired a deep understanding beyond those of today's experts. The EIA, which is considered a premier expert in energy technology, has not yet been forecasting that clean technology will *on average* greatly change the trend in worldwide emissions per dollar of GDP greatly over the next thirty years *even just by 2050*.

III Suggested TSP Emission Scenarios To Guide the CMIP

To suggest scenarios of interest based on the TSP analysis, one can now assume that each of the three inputs evolves independently. To a first-order approximation, this has been true of the historical data. Furthermore, the structures of the IAMs are also suggesting that the correlations between these specific components are not likely to be of first order.[8]

Table 1: Suggested Prime TSP Scenarios

				Pop × (CO_2/Pop)				Pop × (GDP/Pop) × (CO_2/GDP)	
Name	Mnemonic	Pop	CO_2/Pop	@00	$\sum_{21\text{–}00}$	GDP/Pop	CO_2/GDP	@00	$\sum_{21\text{–}00}$
X-Small	[S][S][S]	8.0	3.9	31	2,900	52.2	0.065	27	2,700
Medium	[M][M][M]	10.3	6.4	66	4,200	74.8	0.086	66	4,200
X-Big	[B][B][B]	12.7	10.4	132	6,300	101.1	0.112	143	6,600
	Units:	(bln)	(tCO_2/p/y)	$GtCO_2$	$GtCO_2$	k$/p/y	g/$	$GtCO_2$	$GtCO_2$

Explanations: The scenario naming scheme indicates population, per-capita GDP, and technological pollutiveness, with S (small), M (medium), and B (big). The '@00' indicates the CO_2 emissions in the year 2100; and the summation sign indicates the 79 years of emissions assuming a constant growth rate.

Table 1 describes the cases in which variables reach their 1%, central, and 99% forecasts. It further shows that it matters little whether one forecasts CO_2/GDP or its two components.

[8] Simulations show that shocks to population growth are unlikely to correlate greatly with shocks to per-capita emissions. Even in the IPAT decomposition, emissive technology follows largely exogenous and independent processes; and the IAMs have suggested that the influence of demographic and emissive technology shocks on GDP growth is likely to be small. (It is not so small as to justify neglecting optimal policies, but is small enough in relative magnitude not to alter the conclusions here.) Raftery, Zimmer, Frierson, Startz, and Liu (2017) point out that world population growth is likely less correlated with emissions growth in the future, because most population growth will occur in Sub-Saharan Africa, which starts from a very low base emissions.

The three scenario narratives are simple, monotonic, and easy to explain:

- [S][S][S]: Extremely small population growth, extremely small economic growth, extremely small emissions (big technological progress).
- [M][M][M]: Expected population growth, expected economic growth, expected technological progress.
- [B][B][B]: Extremely big population growth, extremely big economic growth, extremely big emissions (small technology progress).

The RCPs are numbered for their outputs, not their inputs. Nevertheless, the association between total emissions and radiative forcing is strong. The SSP scenarios associate emission scenarios with radiative forcing of

	RCP 2.6	RCP 4.5	RCP 6.4	RCP 7.0	RCP 8.5
$GtCO_2$	1,000	2,700	4,100	5,400	7,800

Thus, the TSP estimated emission numbers suggest that the RCPs in the IPCC AR7 should consider (would result in) no-intervention empission scenarios equivalent to what will output about RCP 4.5 to RCP 7.5, with emphasis on scenarios at or below RCP 6.5. Due to the exponential association, emission scenarios below RCP 4 (or above RCP 8) seem nearly impossible in the absence of miracles. Of course, uncertainties in the physical Earth model could well produce RCPs in excess of 7.0, but those would not be originating from the plausible range of human emissions.

Importantly, because the mapping from CO_2 emissions to radiative forcing is logarithmic (and human emission growth to 2100 is almost surely not), RCP 8.5 (the highest SSP) is far less plausible than RCP 7.0 or RCP 7.5, which in turn is far less plausible than RCP 6.5 (suggested here as a good central and perhaps most plausible emission result [in the absence of intervention]). Equivalently, RCP 4.5 or lower seem currently implausible (suggested here as a useful lower extreme), too. However, the possibility of active intervention would suggest adding some lower scenarios for CMIP consideration, too.

It would also be easy to extend these scenarios. For example, the CMIP could also consider a scenario in which all three inputs first rise and then fall again (say, "[BMS][BMS][BMS]," such as the first 2-3 decades of growth at the 99% bound, then 2-3 decades of growth at the mean, then 2-3 decades of decline at the 1% bound). However, economists have no reason to believe in such inverse U-shaped evolution. Moreover, the global emissions of such a scenario would ultimately end up closer to the central scenario by 2100, but decrease faster thereafter. For space reasons, this paper does not discuss such scenarios.

Furthermore, to span active intervention scenarios, the CMIP could also consider an even lower emission scenario — either by scaling all three components further down or by disproportionally adjusting the emissive-technology progress.

IV Model Comparisons

A TSPs and Similar Time-Series Based Projections

Similar time-series estimations were undertaken by Raftery, Zimmer, Frierson, Startz, and Liu (2017) and Rennert et al. (2022).

Raftery et al focus on estimating an emissions density function from the IPAT components to assess its implications for temperature. They aggregate regional estimates, with data ending in 2010. Per private communication, in the latest Liu and Raftery (2021) update, the model assesses a range from 1,870 $GtCO_2$ to 5,500 $GtCO_2$ from 2020 to 2100 as a 95% interval (with 3,200 $GtCO_2$ as median).

Rennert et al focus on estimating the social cost of capital (and into the year 2300) on behalf of the RFF SCC Initiative. They revisit the SSP inputs in their Section I.A. and discuss the limitations of the probability-free collection of SSP scenarios. They assess a peak of 10 billion people with a 98% range of about 9 billion to 13 billion (visually assessed) by 2100. They report a 99% range of a forecasting model in Müller, Stock, and Watson (2022) of –0.6% to 4.4% per year for the OECD, that increases to about 0% to 5% when augmented with expert opinions. Although the models are based principally on OECD GDP forecasts, they project this reasonably into world GDP. (The non-OECD countries are expected to account for more than 2/3 of the world's emissions before the end of the century.) Their Figure 8 visually suggests that total RFF emissions have a

98% range that is about 5% lower than those under SSP1-26 and 5% higher than those under SSP3-70 — thus, ranging from about from 900 $GtCO_2$ to about 5,700 $GtCO_2$.

Both papers present more ambitious models than the simpler one in my own paper. They attempt to provide specific probability estimates (which they need for further projections of temperature and social cost of carbon, respectively). I limited the TSP model to merely assessing "very unlikely" scenarios (reaching the 1% and 99% levels in all three IPAT identity components). That is, the TSP model in my paper did not take the exact tail probabilities for multi-decade forecasts literally, as it only sought to give generic extreme scenario guidance rather than a true probability distribution. This is intermediate grounds between the probability-less SSPs and the exact probability estimates of Raftery and Rennert.

Nevertheless, and most importantly, it is comforting that the estimates of all three time-series models are by-and-large in good agreement. They are not sensitive. The emission estimates of any of these models would be more likely to be realized than the assessments of the SSPs.

B TSPs and IAMs

An alternative and consistent approach to projecting emissions would be an Integrated Assessment Model (IAM), e.g., as in Nordhaus (1992). Now in its 2023 iteration, reflecting recent climate research, DICE is still the most widely used model. DICE's scientific climate underpinnings are themselves based on the research of the IPCC Earth Science group. Like the CMIP itself, DICE is internally consistent, predictive, and scientific (empirically falsifiable). Nevertheless, IAMs have not been adopted for the CMIP underpinnings, perhaps because outputs are not always immediately intuitive based on inputs, perhaps because of reservations about other functional links made in the model.

The TSPs share with the IAMs that the analysis is largely empirically driven, objective, and replicable. The predictions are falsifiable. TSPs are more generic than any one specific IAM — they are less constrained by a specific structural model. Although it is not entirely clear which method will ultimately predict better (determined by the stability of the structural model vs. the stability of the time-series econometric model), the predictions turn out to be quite similar. To the extent that the goal is to define a wide range of possible scenarios, the TSPs and IAMs seem practically indistinguishable.

This leaves some advantages of the TSPs:

1. They are simpler to estimate and easier to understand.
2. Not being geared towards optimal intervention, they can sidestep some controversial assumptions, such as those related to the specific economic damage function or the presence of one single decision-maker.
3. They do not impose the specific functional forms of a DICE. (Of course, they impose their own.)

The TSPs simply project history forward, as realized in the past. They are geared *only* towards the specific use case at hand here, i.e., coordinating the CMIP onto a reasonable scenario range span of emission paths *in the absence of intervention*. The TSPs cannot analyze other important aspects that only IAMs can — first and foremost, the guiding of the design of optimal carbon policies. For the task at hand, the emission estimates of any of the IAMs would be more plausible than the assessments of the SSPs.

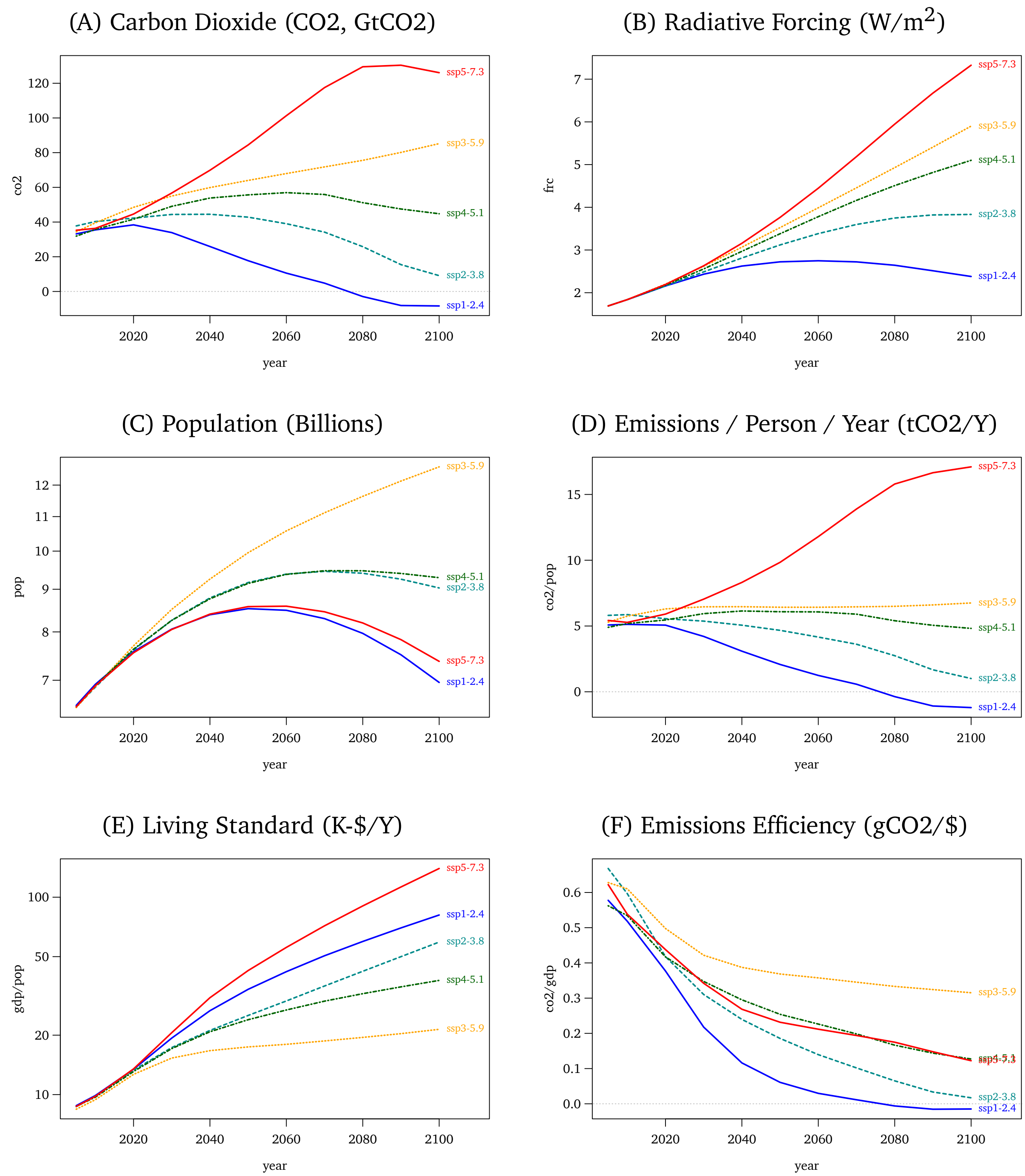
C TSPs vs. SSPs

It is the TSPs that are built on the IPCC's principal motivating statement, also in the IPCC, and not the SSPs: "The purpose is to characterise the demographic, socio-economic and technological driving forces underlying anthropogenic greenhouse gas emissions which cause climate change." This is exactly the IPAT identity that is being modeled by the TSPs.

C.1 SSPs and the IPAT

We can evaluate the SSPs in light of the IPCC motivation, too. The IPAT equations in (1) must hold also within the SSPs. Emissions are exactly determined by population, per-capita income, and emissive technology. Ergo, to describe emissions, any narratives or predictions cannot do more than pin down these three inputs. (The narratives attempt to do so on a deeper causality level.)

Figure 4: SSP-RCP Models



Explanations: These are pathways from the IPCC for the baseline pairings, as in Riahi et al. (2017), https://tntcat.iiasa.ac.at/SspDb/dsd. (SSP3 is marked to pair with a forcing of 5.9 W/m^2, because Riahi et al. (2017) describe it as baseline.)

Figure 4 shows the implied paths of the three series for the five baseline SSP-RCPs. The top row shows emissions and forcing. The bottom two rows show the SSP associations leading to them.

Because the AR6 IPCC SSPs are officially associated with GDP and population estimates (see Table 2), they tie down two of the three variables, $\text{Pop} \cdot \text{GDP}/\text{Pop} = \text{GDP}$. The remaining free variable is CO_2/GDP (or, alternatively, CO_2/Pop), which must be determined by the associated RCP (because the RCP pins down total emissions). Thus, the SSP-RCP paired narratives (with all their deeper causes) cannot do more than pin down the one remaining free variable, emissive technological progress (CO_2/GDP).

Given the quoted population (Panel C) and output per person (Panel E), SSP-RCPs can logically only be about technology forecasts, panels (D) and (F). They show that the critical inputs in SSP1-2.4 and SSP2-3.8 are *radical* technological emission advances. Similarly, SSP2-4.5 scenario is associated with both higher living standards and lower emissions than the dominated SSP4-6.0 scenario, because it assumes faster technology progress.

Unfortunately, it is never entirely clear why these technology associations are necessarily the case. Many of the narratives barely describe their technological progress assumptions. For example, the SSP1 narrative does not explain how its various aspects would or should lead to superior emission-technological progress. In fact, one has to read between the lines to find *any* role for technology — it appears as a *fait accompli* only in "low resource and energy intensity," which contrasts with long narratives about (important) processes about human development.

C.2 Scenario Ranging

Table 2 shows how the IPCC SSPs achieve their spreads across optimistic and pessimistic emissions scenarios vs. how the TSPs achieve their scenario spreads. (The TSP scenarios have been rescaled to correspond to the numbers in the SSP scenarios.)

The right-most column 11 in Panels A and B labels the three components (population, per-capita GDP, and emissions per GDP) relative to the TSP forecasts. Although the SSP scenarios cover total emission ranges similar to the SSS and BBB TSPs, the SSPs do so in combinations that do not span either the TSP extremes *or even their own SSP extremes (xB, xB, xB)*. Instead, the SSPs reach their extreme scenarios by proposing different mixes of extreme values, with some values that the TSP analyses consider nearly impossible.

Table 2: Suggestive Comparison of SSP Scenarios and TSP Scenarios

Panel A: IPCC SSP Scenarios

		by 2100		in 2100 →		IPAT 2100				TSP-like
	frc	cnc	totco2	co2	GDP	Pop	CO_2/Pop	GDP/Pop	CO_2/GDP	Charact-
Units:	W/m^2	ppm	$GtCO_2$	$GtCO_2$	t-$k	bln	tCO_2/P/Y	$/P/Y	g/$	erization
SSP1-26	2.6	432	946	–8	565	7.0	–1.2	81	–0.01	xS, xS, xS
SSP2-45	4.3	567	2,703	9	535	9.0	1.0	59	0.02	MS, xS, xS
SSP3-BL	7.2	834	5,430	85	270	12.6	6.8	21	0.32	B, M, xB
SSP4-BL	6.4	718	4,135	45	352	9.3	4.8	38	0.13	MS, MS, M
SSP5-85	8.7	1,089	7,792	126	1,031	7.4	17.1	140	0.12	xS, xB, M
2010 (IPCC)	2.1	391	n/a	≈37	≈67	≈6.9	≈5.4	≈9.7	≈0.56	

Panel B: Proposed TSP Scenarios

		by 2100		in 2100 →		IPAT 2100				TSP-like
	frc	cnc	totco2	co2	GDP	Pop	CO_2/Pop	GDP/Pop	CO_2/GDP	Charact-
Units:	W/m^2	ppm	$GtCO_2$	$GtCO_2$	t-$k	bln	tCO_2/P/Y	$/P/Y	g/$	erization
[S][S][S]			2,900	31	295	8.0	3.9	52	0.065	S, S, S
[M][M][M]			4,200	66	543	10.3	6.4	75	0.086	M, M, M
[B][B][B]			6,300	132	906	12.7	10.4	101	0.112	B, B, B
2010 (EIA, adj)				39	67	7.0	5.6	9.6	0.58	
2021 (EIA, adj)				42	93	7.9	5.3	11.7	0.45	

Explanations: In the final column, S means "small," M means "medium," and B means "big." "x" means "extra," numbers far beyond the 1%/99% band of the TSP model (in Panel B). The three comma-separated characterizations in Panels A and B are for Population, GDP/Capita, and CO_2/GDP. In Panel C, epsilon means less than 0.0000001%. CDF is the cumulative distribution function.

Panel A is from the SSP database. BL is "baseline," as designated by the IPCC. "frc" is radiative forcing, "cnc" the concentration, and "totco2" the cumulative emissions to 2100. (Different SSP scenarios/models use slightly different input measures for past emissions and GDP.) The free parameter (the assumed technology progress) in column 10 is inferred from its emission forecasts.

Panel B numbers are EIA data. Some EIA numbers in this table had to be adjusted to put them on a comparable basis with their IPCC counterparts (e.g., due to different reporting and recording conventions). Emissions and dollar figures have been rescaled to match the SSP data in 2020. Because the EIA records only fossil-fuel CO_2 emissions, the emission numbers have been scaled up by 19.3% to match the IPCC numbers. The EIA uses a different nominal-base year for its worldwide purchasing-power adjusted GDP figure, again requiring simple rescaling.

Source: The SSP database, `https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=10`, with suggested citation of Riahi et al. (2017).

C.3 Probability Assessments

Like Raftery, Zimmer, Frierson, Startz, and Liu (2017), Liu and Raftery (2021), and Rennert et al. (2022), the TSP model can offer (basic) probability assessments. Unlike its peers, these estimates should be considered only as indicative and taken with a grain of salt. The model confidence assessments are probably overoptimistic because the data-generating processes of the IPAT components will not likely be perfectly stable over the next 80 years or so. Similarly, it is plausible that some of these three series could have fat tails that have not been observed in the realized history used to model them. Nevertheless, characterizing the RCP 4.5-7.0 as an appropriately extremely wide range that is likely to cover future emissions seems to be appropriate.[9]

Recall that the IPCC defines SSPs as outcomes in the absence of intervention, which is also the thought experiment for the time-series model. Table 3 shows probability assessments of the five SSP base scenarios, in light of United Nations population forecasts (Economic and Social Affairs (2022)). It shows that the time-series model judges none of the SSP scenarios to be reasonably plausible. The SSP3, SSP4, and SSP5 are based on implausible worldwide living-standard forecasts — SSP3 and SSP4 are too low, and SSP5 is too high. The SSP-RCP pairings are also based on implausible technology progress — too optimistic in SSP1-26 and SSP2-45 and too pessimistic in SSP3-BL, SSP4-BL, and SSP-85.[10] Emissions in the baseline SSP4-RCP scenario are reasonably plausible only because an implausibly low living standard scenario is multiplied by an implausibly pessimistic emissive technology progress scenario.

Although the IPCC does not want to assign probabilities (or clear exogenous causes) to its scenarios, it is unclear why the SSPs should be pushing the CMIP models for coordination on scenarios that empirical macro-history suggests to be implausible. The TSP projections suggest that some of the SSP scenarios may be about as likely to occur as climate-altering asteroid impacts, supervolcano eruptions, nuclear war, or disastrous new types of epidemics — all of which would also have dramatic impacts on population and GDP.

[9] There are of course many other uncertainties — specifically those relating to the global temperature increase effects in the physical model and global economic damages that these emissions will cause. Analyzing the effects of RCPs higher than 7.0 *not based on emission scenarios* is reasonable.

[10] The SSP combinations also seem odd. The SSP evolutions are only halfway plausible even if one believes that draws have infinite variance — itself not a plausible conjecture.

Table 3: Time Series Probability Assessment

Panel A: Probability Assessments of Official SSP Pairings of GDP and Population

		Population	CDF	GDP/Pop	CDF
Sustainability	SSP1	7.0	0.1%	81	70%
Middle Road	SSP2	9.0	2%	59	6%
Reg Rivalry	SSP3	12.6	15%	21	ϵ
Inequality	SSP4	9.3	20%	38	0.00055%
Fossil-Fuel	SSP5	7.4	92%	140	99.998%

Panel B: SSP-RCP Combinations Probability Assessments

		CO_2/Pop	CDF	CO_2/GDP	CDF
Sustainability	SSP1 -RCP 26	–1.2	0	—0.01	0
Middle Road	SSP2 -RCP 45	1.0	ϵ	0.02	ϵ
Reg Rivalry	SSP3 -RCP BL	6.8	62%	0.32	$1-\epsilon$
Inequality	SSP4 -RCP BL	4.8	8%	0.13	99.98%
Fossil-Fuel	SSP5 -RCP 85	17.1	$1-\epsilon$	0.12	99.83%

Explanations: CDF is the location in the cumulative distribution function from a time-series analysis projecting the last 30 years forward to 2100. Epsilon means less than 0.0000001%. BL is "baseline," as designated by the IPCC. Equivalent numbers for 2021 are a population of 7.9 billion, GDP of $93 trillion, and emissions of 42 $GtCO_2$. Not shown, the technology forecasts in the lower panel are very similar to those by the EIA over the next 30 years. They are not ignorant of clean-energy progress. Data Sources: The SSP database, https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=10, with suggested citation of Riahi et al. (2017). Population Forecasts from the United Nations. Time-series analysis for ratios are based on data from the U.S. Energy Information Agency (EIA).

V Conclusion

My paper has examined the SSPs with respect to natural associations, logical consequences, economic identification, clarity of exogeneity and empirical measurements (p.15); and contrasted them with a simpler time-series based approach, such as one that is similar to those in Raftery, Zimmer, Frierson, Startz, and Liu (2017) or Rennert et al. (2022). It suggests that the use of such models (or an IAM) would return both IPCC climate models and referencing economic research papers to the underpinnings of a positive economics approach (Friedman (1953)). The time-series models can yield simple, replicable, less subjective, and more plausible emission scenarios. The plausible emission scenario range suggested by a simplified TSP version here — which would suggest focusing on what will likely result in a CMIP output of RCP 6.5 with a range from RCP 4.5 to RCP 7.0 —- are also largely consistent with independent forecasts from the EIA (and other expert technology forecasters) as well as forecasts from integrated assessment models. The forecasts could be easily updated every year.

The time-series characterizations would be easy to explain to scientists and non-scientists:

- Modest global warming will occur if the world population grows less (only to 8 billion), the world economy grows slower (only by 1.5% per year), and clean energy advances faster (doubling efficiency every 20-25 years). In this case, the world may emit 3,000 $GtCO_2$ cumulatively from 2020 to 2100 and reach an atmospheric CO_2 concentration of about 600 ppm (roughly the equivalent of RCP 4.5).

- A medium global warming scenario will occur if the world population grows as demographers expect (to 10 billion), the world economy grows as it has (by 2.0% per year), and clean energy advances as it has (doubling efficiency every 25-30 years). In this case, the world may emit 4,500 $GtCO_2$ and reach an atmospheric CO_2 concentration of about 750 ppm (roughly the equivalent of RCP 6.5).

- Strong global warming will occur if the world population grows more (to 12.7 billion), the world economy grows faster (by 2.4% per year), and clean energy advances slower (doubling efficiency only every 30-35 years). In this case, the world may emit 6,500 $GtCO_2$ and reach an atmospheric CO_2 concentration of about 900 ppm (roughly the equivalent of RCP 7.0).

Due to their logarithmic nature, anthropogenic emission scenarios that would lie beyond the RCP 4.5 to RCP 7.0 range (using the CMIP naming convention based on *expected* radiative forcing) seem implausible.[11] The time-series scenarios would be easier for policymakers to understand. They would point policymakers to think about more forces that could influence the three necessary ingredients: population, income, and emission efficiency. These forces could include those mentioned in the SSP narratives, but would not be limited by them. In particular, accelerating clean energy technology could causally reduce worldwide emissions, and possibly even in the absence of other forces described in the narratives.

The case for simple statistical time-series scenarios is thus not even about disputing the SSP narratives. It is merely about focusing the CMIP on the immediately necessary causality layer that exactly fulfills the IPCC's stated intent to "characterize the demographic, socio-economic and technological driving forces underlying anthropogenic greenhouse gas emissions..." Recognized or not, the SSP narratives always had to project emissions through these three forces. The SSP analysis could then potentially offer up deeper causes, linking aspects like sustainability, rivalry, or inequality more clearly into these necessary channels. However, there is a deep gulf that remains before the SSPs can provide plausible testable economic hypotheses.

[11] A fourth scenario could consider quickly rising emissions for the first 20-30 years, followed by quickly declining emissions in subsequent years. With some additional assumptions, all assessments could be expanded to allow for convex or concave emission paths and be extended to other greenhouse gases.

References

Carleton, Tamma et al. (2022). "Valuing the global mortality consequences of climate change accounting for adaptation costs and benefits". In: *The Quarterly Journal of Economics* 137.4, pp. 2037–2105.

Cochrane, John H. (1988). "How big is the random walk in GNP?" In: *Journal of Political Economy* 96.5, pp. 893–920.

Commoner, Barry (1972). "CLOSING CIRCLE-REPLY". In: *Science and Public Affairs-Bulletin of the Atomic Scientists* 28.5, p. 17.

Dellink, Rob, Jean Chateau, Elisa Lanzi, and Bertrand Magné (2017). "Long-term economic growth projections in the Shared Socioeconomic Pathways". In: *Global Environmental Change* 42, pp. 200–214. URL: https://www.sciencedirect.com/science/article/pii/S0959378015000837.

Easterly, William (2003). "Can foreign aid buy growth?" In: *Journal of economic Perspectives* 17.3, pp. 23–48.

— (2009). "Can the west save Africa?" In: *Journal of economic literature* 47.2, pp. 373–447.

Easterly, William and Ross Levine (1997). "Africa's growth tragedy: policies and ethnic divisions". In: *The quarterly journal of economics*, pp. 1203–1250.

Economic, United Nations Department of and Population Division Social Affairs (2022). *World Population Prospects: Summary of Results.* Tech. rep. UN DESA/POP/2022/TR/NO.3.

Ehrlich, Paul R and John P Holdren (1972). "Critique". In: *Bulletin of the Atomic Scientists* 28.5, pp. 16–27.

Friedman, Milton (1953). "The methodology of positive economics". In.

Galor, Oded (2011). *Unified growth theory*. Princeton University Press.

Henderson, J. Vernon, Adam Storeygard, and David N. Weil (2012). "Measuring economic growth from outer space". In: *American Economic Review* 102.2, pp. 994–1028. URL: https://www.aeaweb.org/articles?id=10.1257/aer.102.2.994.

Hsiang, Solomon and Robert E Kopp (2018). "An economist's guide to climate change science". In: *Journal of Economic Perspectives* 32.4, pp. 3–32.

IPCC, Climate Change et al. (1995). "Report of the intergovernmental panel on climate change". In: *IPCC report, Geneva, Switzerland, 64p*. URL: https://www.ipcc.ch/report/ar6/syr/downloads/report/IPCC_AR6_SYR_SPM.pdf.

Kriegler, Elmar et al. (2012). "The need for and use of socio-economic scenarios for climate change analysis: a new approach based on shared socio-economic pathways". In: *Global Environmental Change* 22.4, pp. 807–822. URL: https://www.sciencedirect.com/science/article/pii/S0959378012000593.

Liu, Peiran R and Adrian E Raftery (2021). "Country-based rate of emissions reductions should increase by 80% beyond nationally determined contributions to meet the 2 C target". In: *Communications earth & environment* 2.1, p. 29.

Lutz, Wolfgang, William P. Butz, and K.C. Samir (2017). *World population & human capital in the twenty-first century: An overview*. Oxford University Press.

Moss, Richard H et al. (2010). “The next generation of scenarios for climate change research and assessment”. In: *Nature* 463.7282, pp. 747–756. URL: https://www.nature.com/articles/nature08823.

Müller, Ulrich K, James H Stock, and Mark W Watson (2022). “An econometric model of international growth dynamics for long-horizon forecasting”. In: *Review of Economics and Statistics* 104.5, pp. 857–876.

Nordhaus, William D. (1992). *The ’DICE’ Model: Background and Structure of a Dynamic Integrated Climate-Economy Model of the Economics of Global Warming*. Tech. rep. Yale University, Cowles Foundation.

Nordhaus, William D. and Joseph Boyer (2003). *Warming the world: economic models of global warming*. MIT press.

Noy, Ilan (Oct. 2023). “Economists are not engaged enough with the IPCC”. In: *Nature Climate Action* 33.

O’Neill, Brian C et al. (2014). “A new scenario framework for climate change research: the concept of shared socioeconomic pathways”. In: *Climatic change* 122, pp. 387–400. URL: https://link.springer.com/article/10.1007/s10584-013-0905-2.

Raftery, Adrian E, Alec Zimmer, Dargan MW Frierson, Richard Startz, and Peiran Liu (2017). “Less than 2 C warming by 2100 unlikely”. In: *Nature climate change* 7.9, pp. 637–641.

Rennert, Kevin et al. (2022). “The social cost of carbon: advances in long-term probabilistic projections of population, GDP, emissions, and discount rates”. In: *Brookings Papers on Economic Activity* 2021.2, pp. 223–305.

Riahi, Keywan et al. (2017). “The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview”. In: *Global environmental change* 42. The database as in https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=10, pp. 153–168. URL: https://pdf.sciencedirectassets.com/271866/1-s2.0-S0959378016X00076/1-s2.0-S0959378016300681.

Spolaore, Enrico and Romain Wacziarg (2022). “Fertility and modernity”. In: *The Economic Journal* 132.642, pp. 796–833.

A Appendix: SSP Narratives

SSP1 Sustainability – Taking the Green Road (Low challenges to mitigation and adaptation): The world shifts gradually, but pervasively, toward a more sustainable path, emphasizing more inclusive development that respects perceived environmental boundaries. Management of the global commons slowly improves, educational and health investments accelerate the demographic transition, and the emphasis on economic growth shifts toward a broader emphasis on human well-being. Driven by an increasing commitment to achieving development goals, inequality is reduced both across and within countries. Consumption is oriented toward low material growth and lower resource and energy intensity.

SSP2 Middle of the Road (Medium challenges to mitigation and adaptation): The world follows a path in which social, economic, and technological trends do not shift markedly from historical patterns. Development and income growth proceeds unevenly, with some countries making relatively good progress while others fall short of expectations. Global and national institutions work toward but make slow progress in achieving sustainable development goals. Environmental systems experience degradation, although there are some improvements and overall the intensity of resource and energy use declines. Global population growth is moderate and levels off in the second half of the century. Income inequality persists or improves only slowly and challenges to reducing vulnerability to societal and environmental changes remain.

SSP3 Regional Rivalry – A Rocky Road (High challenges to mitigation and adaptation): A resurgent nationalism, concerns about competitiveness and security, and regional conflicts push countries to increasingly focus on domestic or, at most, regional issues. Policies shift over time to become increasingly oriented toward national and regional security issues. Countries focus on achieving energy and food security goals within their own regions at the expense of broader-based development. Investments in education and technological development decline. Economic development is slow, consumption is material-intensive, and inequalities persist or worsen over time. Population growth is low in industrialized and high in developing countries. A low international priority for addressing environmental concerns leads to strong environmental degradation in some regions.

SSP4 Inequality – A Road Divided (Low challenges to mitigation, high challenges to adaptation): Highly unequal investments in human capital, combined with increasing disparities in economic opportunity and political power, lead to increasing inequalities and stratification both across and within countries. Over time, a gap widens between an internationally-connected society that contributes to knowledge- and capital-intensive sectors of the global economy, and a fragmented collection of lower-income, poorly educated societies that work in a labor intensive, low-tech economy. Social cohesion degrades and conflict and unrest become increasingly common. Technology development is high in the high-tech economy and sectors. The globally connected energy sector diversifies, with investments in both carbon-intensive fuels like coal and unconventional oil, but also low-carbon energy sources. Environmental policies focus on local issues around middle and high income areas.

SSP5 Fossil-fueled Development – Taking the Highway (High challenges to mitigation, low challenges to adaptation): This world places increasing faith in competitive markets, innovation and participatory societies to produce rapid technological progress and development of human capital as the path to sustainable development. Global markets are increasingly integrated. There are also strong investments in health, education, and institutions to enhance human and social capital. At the same time, the push for economic and social development is coupled with the exploitation of abundant fossil fuel resources and the adoption of resource and energy intensive lifestyles around the world. All these factors lead to rapid growth of the global economy, while global population peaks and declines in the 21st century.

Local environmental problems like air pollution are successfully managed. There is faith in the ability to effectively manage social and ecological systems, including by geo-engineering if necessary.

$\mathcal{B}$ One Base Narrative (SSP1-2.6) Discussed in Detail

It is perhaps instructive to describe the gulf between the narrative and its emissions through one of the SSPs. Even if some statements can be interpreted, as a set, the statements in the narratives do not seem geared to explain the necessary and sufficient conditions.

For example, return to the low-emission scenario SSP1-2.6, which is associated with zero emissions in about 2090. Importantly, the IPCC associates SSP1-2.6 with *higher* per-capita income than SSP2, SSP3, and SSP4. Puzzlingly, the SSP1 narrative assumes the counterproductive *superior* living-standard growth, offset by even more radical emission-technological change. Why it would be *this* combination, in particular, that would or should lead to the world's plausible low-emission scenario seems at first unclear. The SSP1 narrative may give answers:

> **SSP1 Sustainability – Taking the Green Road (Low challenges to mitigation and adaptation):** The world shifts gradually, but pervasively, toward a more sustainable path, emphasizing more inclusive development that respects perceived environmental boundaries. Management of the global commons slowly improves, educational and health investments accelerate the demographic transition, and the emphasis on economic growth shifts toward a broader emphasis on human well-being. Driven by an increasing commitment to achieving development goals, inequality is reduced both across and within countries. Consumption is oriented toward low material growth and lower resource and energy intensity.

The first ingredient of the IPAT identity is population. The SSP1 narrative statement about faster demographic transitions is indeed nearly synonymous with lower population growth. At this point, a part of the narrative seems to have (logically) covered population growth.

This makes it puzzling what the further related assertions in the narrative are intended to convey. Are they necessary? Are they sufficient? Are they the deeper causes that bring about the demographic transition? If so, are they merely elaborations that could be omitted? Do they explain higher or lower consumption per capita and better or worse technology?

The assertions in the narrative are frustratingly vague, possibly inducing different understandings by different readers. For example, reading individual assertions:

- What does "inclusive development" exactly mean? Inclusivity means different things to different audiences. Is it every type of inclusivity or just some types of inclusivity that are considered here? Could it be clarified to induce *the same* clear understanding by most readers? Exactly which IPAT component(s) would it alter and in which direction? Is it a first-order quantitative aspect (cause or correlate) of world emissions and what is the evidence?

- What does "respects perceived environmental boundaries" exactly mean? Is this stating that people worldwide are becoming more environmentally concerned and active, or are there specific (sharp) boundaries meant here? Exactly which IPAT component(s) would it alter and in which direction? Is it a first-order quantitative aspect (cause or correlate) of world emissions and what is the evidence?
- How do "educational and health investments" play a role? Exactly which IPAT component(s) would it alter and in which direction? Could health investments not decrease (as assumed) but also increase population by 2100 — as they have in some of the poorest countries in the past?
- What is the role of "the emphasis on economic growth shifts towards a broader emphasis on human well-being"? Does this mean a reduction or an increase in GDP per capita? (The standard traditional economic growth measure in SSP1-2.6 is *superior* to those of higher emission scenarios, except SSP5-8.5.)
- How would "[by] increasing commitment to achieving development goals, inequality is reduced both across and within countries" play a role? Exactly which IPAT component(s) would across-country inequality reductions alter, in which direction, and how important and influential would this be on worldwide emissions? Exactly which IPAT component(s) would within-country inequality reductions alter and in which direction? Is it the commitment or the development that matters? Would development goals have to be more successful than such efforts have been in the past (Easterly (2003), Easterly (2009), Easterly and Levine (1997), etc.) in reducing inequality?
- How does inequality reduction reduce global emissions? Of course, less inequality *could* lower emissions — but it could also raise emissions. Unlike economic activity, measured as GDP per person, inequality is not usually seen as a first-order (IPAT) determinant of emissions (e.g., Galor (2011), Spolaore and Wacziarg (2022)). Are worldwide emissions a function of poverty or inequality?

C Appendix: Correlations in Ratio Predictions

Negative auto-correlation and cross-correlations can push the CO_2 path more towards the center. The bigger concern for defining ranges that would be too limited to span possible outcomes is that positive series correlations can push the CO_2 path more toward extremes (both higher and lower).

The most well-known correlation concerns living standards and population growth. When living standards have increased, population growth has declined. This pushes towards less extreme scenarios.

Higher living standards correlate positively with technology (incl. basic technology such as better insulation and solar-cell deployments). To the extent that better technology emits less (per dollar of GDP), this also pushes towards less extreme scenarios. However, the data suggest residual positive autocorrelation in emissions per dollar, pushing towards more extreme scenarios.

Richer people consume more and this can increase the emissions per person. There is no notable autocorrelation. Predicting emissions per person (rather than its components) takes the cross-correlation (and autocorrelation in emissions per dollar) into account. And, as the next table shows, it barely changes higher emission predictions.