Supplementary Information

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I. **ISEEC1: Summary**

ISEEC1 consists of two coupled models: the Natural Systems Model (NSM) and the Social Systems Model (SSM). Carbon emissions simulated by the SSM serves as input to simulate CO_2 concentration and surface temperature trends by the NSM. In turn, the simulated surface temperature trends from the NSM influences the simulated energy generation and carbon emissions in the SSM via societal response to climate risks.

The single major external input to ISEEC1 is the global GDP (Gross Domestic Product). Using this input, ISEEC1 estimates the total energy generation to sustain the economy and its growth, CO_2 emissions due to energy generation, warming due to CO_2 emissions, and societal actions in response to the warming to reduce CO_2. Our primary focus is to illustrate socio-economic-energy-climate interactions resulting from fossil fuel consumption. Towards this focused objective, we prescribe from published sources, climate forcing terms that are extraneous to our study, such as radiative forcing for non-CO_2 greenhouse gas species, radiative forcing due to aerosols that are also major sources of air pollution, and CO_2 emission from land use and land changes (e.g., deforestation and biomass burning). However, we coupled portions of non-CO_2 forcings with fossil fuel use.

The model simulations begin from the year 1850 and extend to 2100. The SSM calculates the total energy generated to sustain the economy. For the historical period (up to 2015), the SSM adopts published values of total energy generation and simulates the relative fraction of fossil fuels and renewable sources. For the period beyond the present (starting from 2016), it uses global GDP as input to estimate total energy generation, assuming future improvement of energy intensity. Most importantly, it simulates the relative fraction of fossil fuels and renewable fuels that contribute to the total energy generation. This relative fraction depends on societal, policy, and technological responses to the global warming level, an output from by NSM component of ISEEC1. The NSM uses CO_2 emissions calculated by the

SSM to simulate CO_2 atmospheric concentration as well as the radiative forcing due to CO_2, the global warming level.

The primary external input to ISEEC1 is historical and projected global GDP. To power the growing economy during the historical period, energy consumption increases proportionately with GDP, mainly in fossil fuels. The emission of greenhouse gases (GHGs) and aerosols by fossil fuels has the net effect of warming the climate. In response to observed climate damages and projected future risks, society responds by switching to zero-emission renewables. But the speed of transition, in ISEEC1 formulation, is constrained by inertia in four components of the human-nature system: the inertia of society to translate climate risks into public concerns and policy actions; inertia in developing new renewable technologies followed by the inertia in scaling up the technologies to global scale; inertia in the natural carbon cycle to respond to emission drawdown, and lastly the inertia in the coupled ocean-cryosphere-atmosphere climate system. A system of 11 time-dependent differential equations was developed and fully coupled to account for the two-way interactions. The formulation of equations and parameter choices were validated by comparing simulated quantities with observed evolution of technologies, fossil fuel use, CO_2 emission, CO_2 concentration, and global temperatures from 1900 to 2015.

The novel aspects of ISEEC1 is its two-way coupling between the social and natural systems. The total energy generation and the shift from fossil fuels to renewables for energy generation are formulated to be dependent on the responses of social/economic systems to observed warming. These responses include:

- Societal Response for climate actions based on scientific findings and observed data since climate change is happening now and is emerging beyond the climate/weather noise.
- Policy Response in anticipation of or after Societal Response.

- Scaling up of existing technologies to meet policy mandates.
- Development of new carbon-free energy technologies.
- Scaling-up of these technologies worldwide also called Technology Diffusion.
- Start-up investment to boost the growth of new technologies.

II. ISEEC2: Background on Inequality and Climate Justice

The mitigation/adaptation feedbacks alter global energy demand and structure and the associated emission of GHGs and aerosols, which are fed into the core module (ISEEC1) as input. The output from ISEEC1 is temperature change, which would then be fed into the adaptation module accounting for global inequality introduced here. Together, ISEEC1 with the new adaptation module, forms ISEEC2 (Figure 1), which was designed to demonstrate the synergy and conflict between mitigation and adaptation.

As explained in the text, ISEEC2 divides the global population into three groups, or say, three-worlds based on their income, wealth, and energy consumption. The Three-World Demographics and Inequalities are shown in Figure SII.1 e.

The first face concerns the disproportionate contribution to emissions of CO_2. Roughly 50% of the climate emissions are due to the wealthiest 1 billion, while the poorest 3 billion contribute just 5% to 10% (Dasgupta and Ramanathan, 2015; Our World in Data). The population can also be classified under the World Bank's income category: High Income (1.2 billion people); Upper-Middle Income (2.6 billion people); Lower-Middle Income (3 billion people) and Lower Income (0.7 billion people).

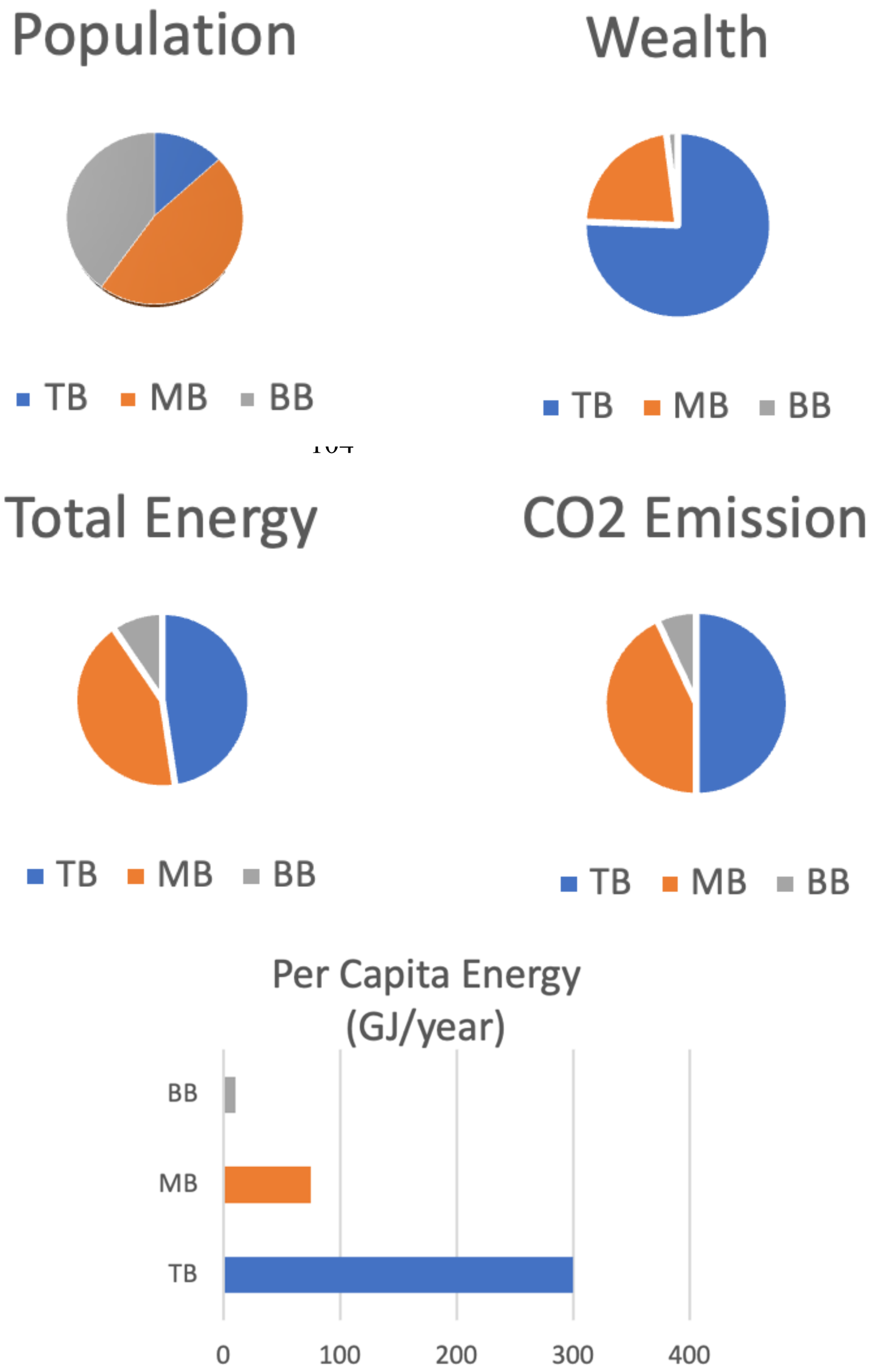

Figure SII.1: Inequality Demographics of the Three Worlds (2016).

Table SII.1. Three-World Demographics and Inequalities (data as presented in Figure SII.1).

group	Population (billion)	CO2 Emission	Per Capita Energy (GJ/year)	Total Energy	Wealth
TB	1	50%	300	50%	75.60%
MB	3.5	43%	75	45%	22.40%
BB	3	7%	10	5%	2%

The high and upper-middle income constituting 51% of the total population (3.8 billion) emit 86% of the global CO_2 while the lower income group (49% of the population, i.e., 3.5 billion) emit only 14%. The lower income group of 0.7 billion emitted just 0.5%, while the high-income group of 1.2 billion people emitted 38% (all statistics for 2016 from Our World in Data).

The bottom three billion is 40% of the total population but own just 2% of the wealth, while the top one billion own 75.6% of the wealth and the middle 3.5 billion own 22.4% (Our World In Data; Piketty, 2022). The first face of equality, with respect to climate change, is the historical contribution by the three population groups to climate change. For the 1990 to 2015 period, the wealthiest 10% (~630 million people) contributed 52% of cumulative carbon emissions, a more relevant metric for climate change, while the poorest 50% (~3.1 billion people) earned less than $5.50/day contributed only 4% and the percent growth in their emissions during this period was near zero. The top billion (TB) focus rightfully on mitigation (Otto et al., 2019) to reduce the longer-term consequences such as sea level rise.

The second face of inequality concerns vulnerability to the resulting climate change. The impacts of climate change, such as droughts, floods, and heat waves, will be felt disproportionately by the poorest 50% (about 3.8 billion), mainly living in rural areas with limited to marginal access to energy, education, and finances (IPCC-AR6-WGII, 2021). Independently a few other factors link global warming directly to increasing economic inequality between the Top Billion and the Bottom Billions. First is that agriculture yield drops predictably with an increase in soil and air temperatures. In addition, air pollution from fossil fuels (ozone and soot) also decreases yield. For example, in India, wheat yields from 1980 to 2010 decreased by 36% due to climate change and air pollution (Burney & Ramanathan, 2014). Globally it has been estimated that growth in agriculture productivity has decreased by as much as 21% since the 1960s due to global warming, with much more significant decreases in warmer countries in Africa, Asia, and Latin America (Ortiz-Boba et al., 2021). Lastly, global warming in climatologically warmer countries, such as South Asia, Africa, and Latin and Central America, has been shown to damage national GDP by as much as 17% to 31% (Diffenbaugh & Burke, 2019; Burke et al., 2015). This exacerbates climate-related intra-generational inequity since most of the poorer three billion live in tropical warmer countries.

The third inequality face concerns the lack of access to clean energy for climate adaptation. The lack of access arises from three sources: Lack of modern sources of energy such as electricity or gas; Lack of continuous (all hours of the day) supply of electricity or gas; Affordability of reliable sources of energy is also an issue. In the short term, adaptation would be the highest priority for the BB since they are not contributing much to the present emission and are the most vulnerable to ongoing climate change. The rural population vulnerable to climate change is close to 3.4 billion (IPCC, AR6 WGII, SPM.C.2.9). Substantial increase in energy access is a crucial issue for this population since it is urgently needed to cope with and adapt to warming-induced climate risks: Heat stress (energy for a fan or refrigerator; access to freshwater wells); climate-smart agriculture to cope with droughts (e.g., pumping water from aquifers and tractors to replace all the hard farm labor); protecting homes against flooding and fires; to name a few.

Supplement References

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Supplement Table

Table S1. Key statistics of the nine cases considered in this study. The full time series of CO_2 emission, CO_2 concentration and simulated temperature are presented in the figures.

Case name	Baseline	Baseline+Adaptation	Baseline+Adaptation+W/O_CJ	CO_2 mitigation	CO_2 mitigation+Adaptation	CO_2 mitigation+Adaptation+W/O_CJ	Full mitigation	Full mitigation+Adaptation	Full mitigation+Adaptation+W/O_CJ
max emission (Gt)	57	133	170	44	66	77	44	57	60
year reaching max emission	2050	2050	2064	2024	2036	2037	2024	2033	2035
year 2100 emission (Gt)	43	94	146	-26	-27	31	-17	-21	15
year 2100 cumulative emission (Gt)	6453	10933	13561	3443	4111	6577	3628	4240	5484
cumulative emission from 2015 to 2100 (Gt)	4237	8717	11345	536	1041	4361	1143	1726	3268
max concentration (ppm)	577	806	952	443	476	572	447	473	517
year reaching max concentration	2100	2100	2100	2043	2048	2100	2046	2050	2100
year 2100 concentration (ppm)	577	806	952	374	392	572	407	430	517
max temperature (ºC)	4.1	6.1	7.0	2.4	2.9	3.6	1.9	2.1	2.6
year reaching max temperature	2100	2100	2100	2072	2065	2100	2088	2087	2100
year 2100 temperature (ºC)	4.1	6.1	7.0	2.2	2.5	3.6	1.9	2.1	2.6

Supplement Figures

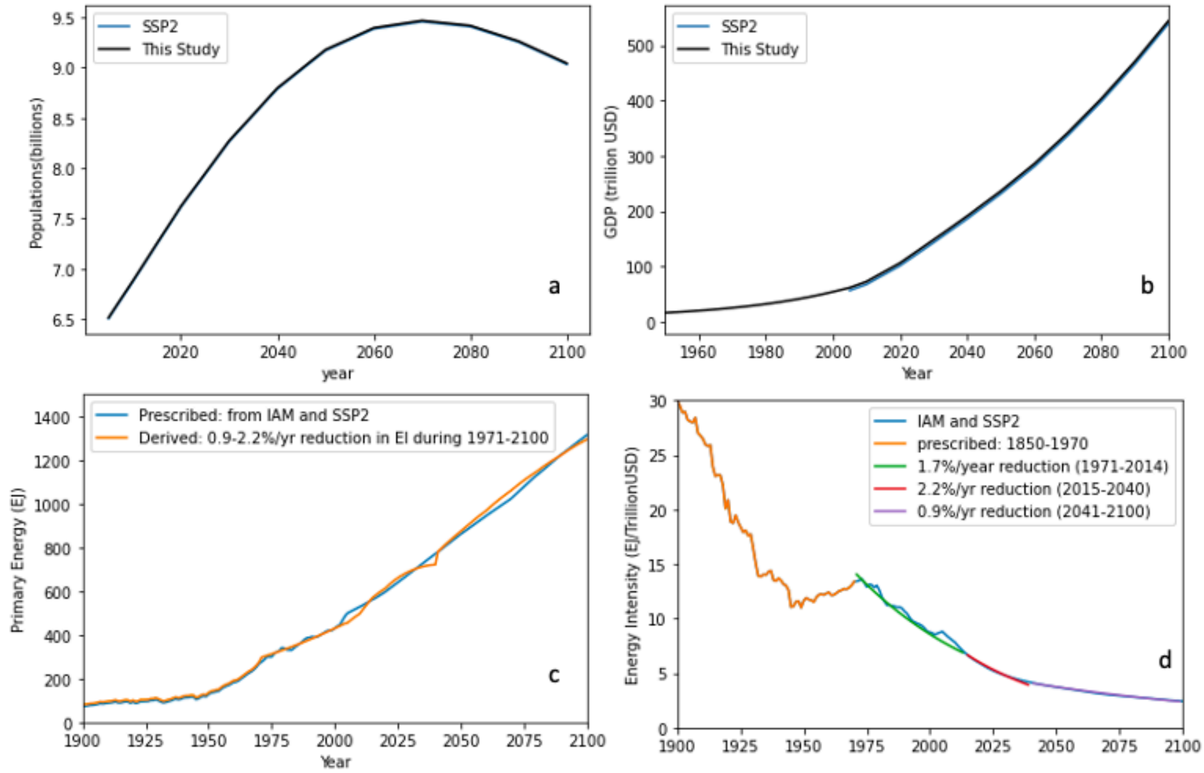

Figure S1. Underlying social economic assumptions in the SSP scenario taken as input to ISEEC2. (a) Population. (b) GDP. (c) total Primary Energy. (d) Energy intensity (the ratio of c and b).

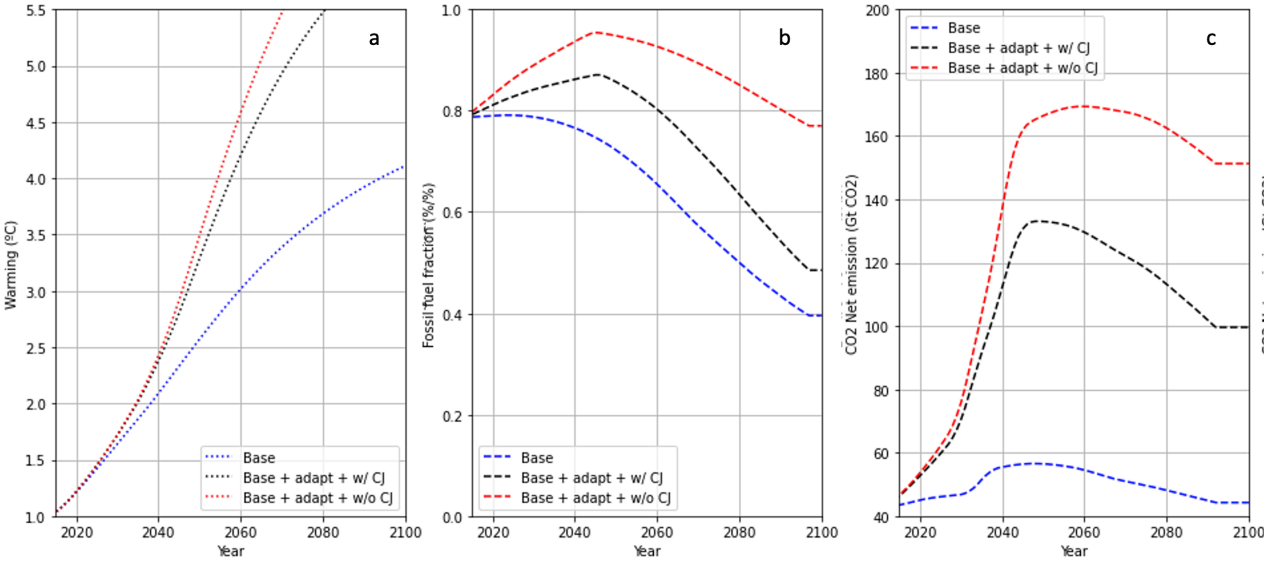

Figure S2. Same as Figure 2 and Figure 3, but for the unrealistic and illustrative baseline case.

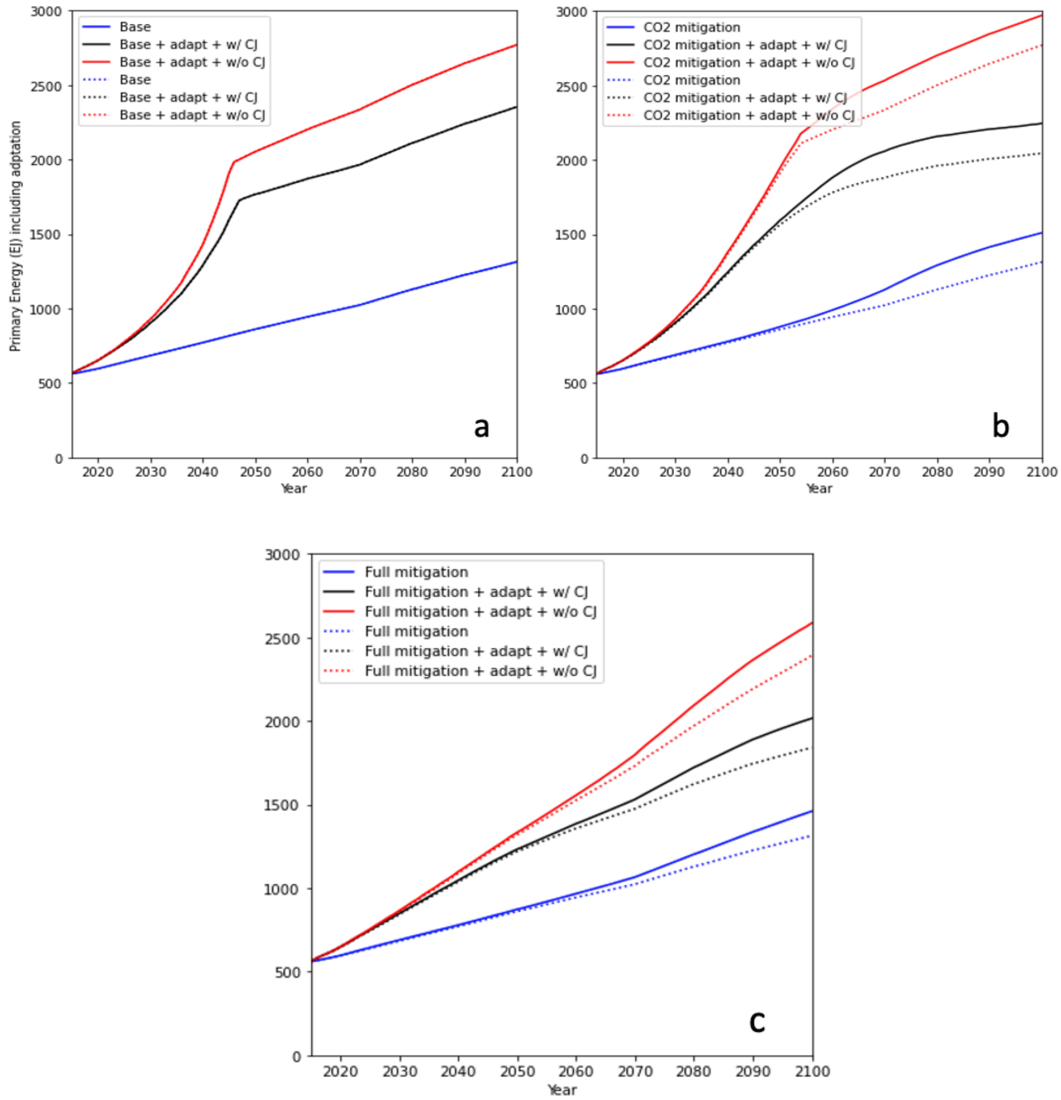

Figure S3. Total PE simulated for all cases. Solid lines include ACE and dotted lines do not include ACE.

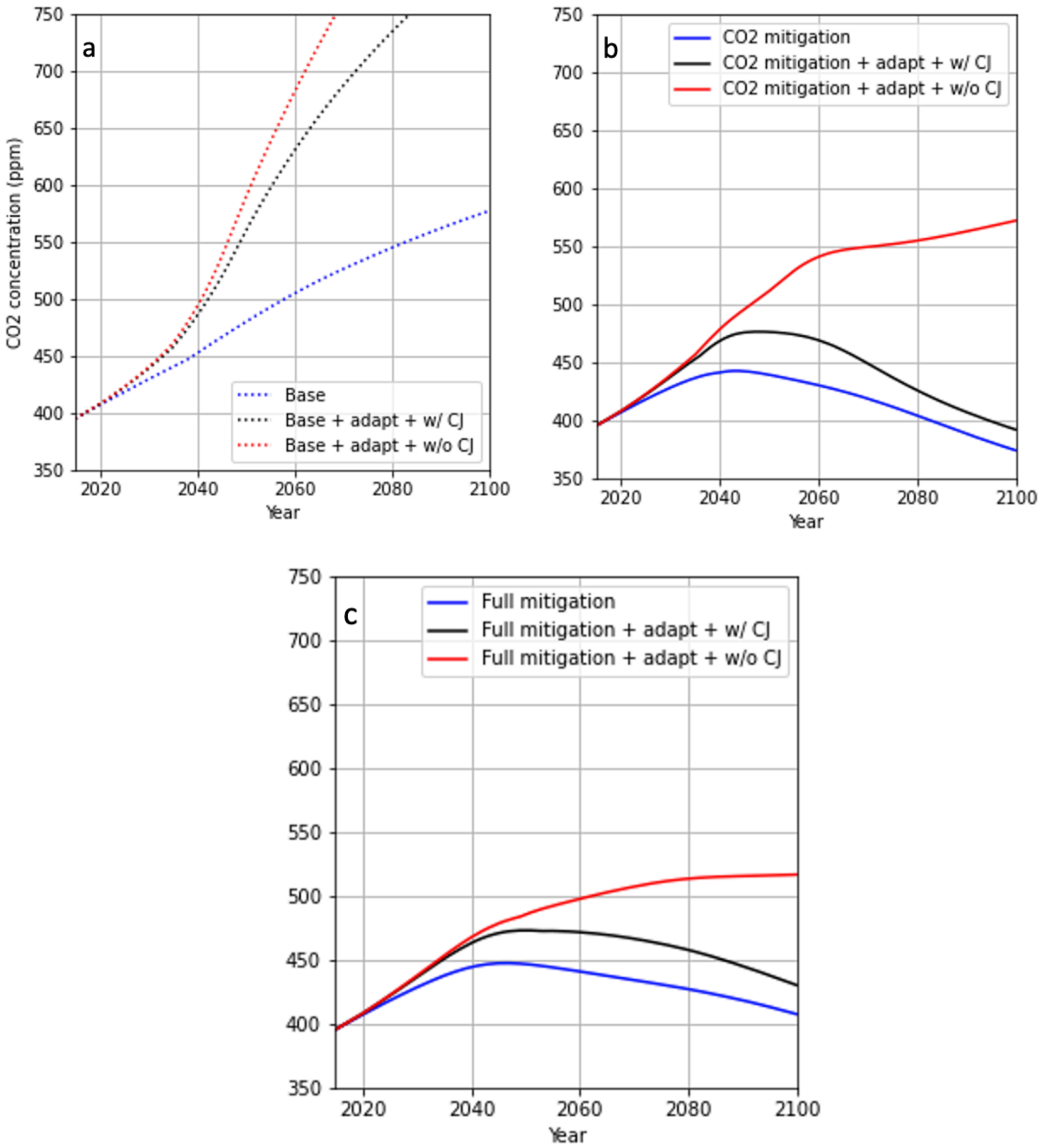

Figure S4. Simulated CO_2 concentration. (a) blue: baseline warming without mitigation; black baseline warming including adaptation; red: baseline warming including adaptation and without CJ. (b) same as (a) but with CO_2 mitigation. Note that this case has some non-CO_2 mitigation coupled with decarbonization. (c) Same as (b), but for full mitigation including additional explicit measures to reduce SLCPs.

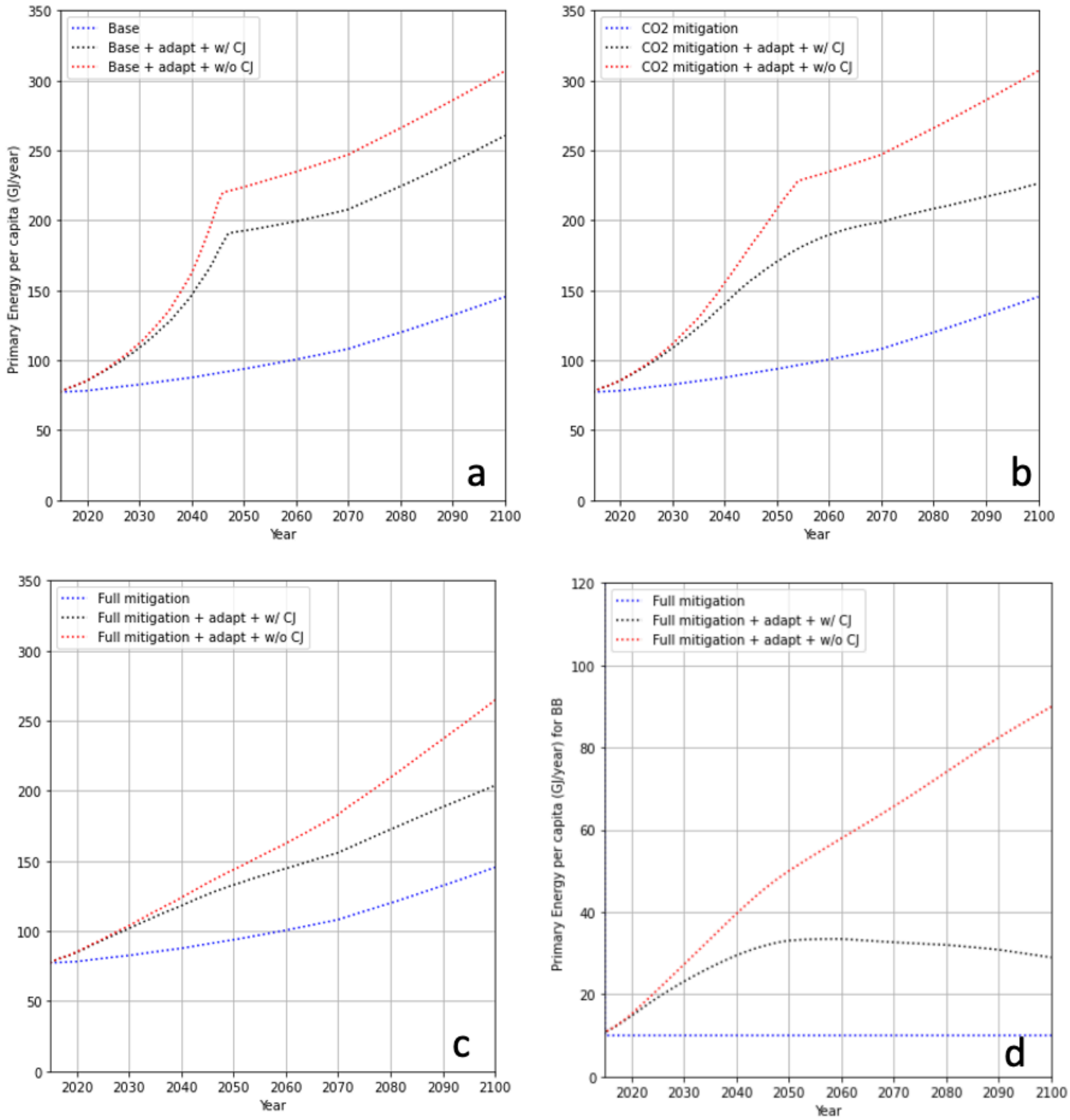

Figure S5. (a-c) Same as Figure S2, but for per capita PE (not including ACE) of whole population. (d) same as (c), but for BB (note the smaller y-axis range).