nature portfolio

https://doi.org/10.1038/s41893-021-00826-z

Supplementary information

Modelling human–natural systems interactions with implications for twenty-first-century warming

In the format provided by the authors and unedited

Supplementary Information
for

Modeling human-natural systems interactions: Implications for 21st-century warming trends

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Nature Sustainability

Part 1 (*S1*): Full technical description of ISEEC (Pages 1 to 19)

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Part 1

Full technical description of ISEEC

including 2 supporting tables and 4 supporting figures

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1. ISEEC Model Architecture

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

The single external input to ISEEC is global Gross Domestic Product (GDP). Using this input, ISEEC estimates the total primary energy supply (TPES; hereafter referred to as primary energy, PE) needed to sustain the economy and its growth, CO_2 emissions due to PE, 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 due to non-fossil sources, such as radiative forcing for non-CO_2 greenhouse gases, radiative forcing due to aerosols that are also major sources of air pollution, and CO_2 emissions from land use and land changes (e.g., deforestation and biomass burning). However, a portion of the above non-CO_2 forcing terms are also emitted by fossil fuels and we account for these forcings with fossil fuel use.

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

The novel aspects of ISEEC are the following:

i. Two-way coupling between the social and natural systems.

The primary energy and the shift from fossil fuels to renewables for PE 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[1].
- The scaling-up of these technologies worldwide also called Technology Diffusion.
- Start-up investment to boost the growth of new technologies.

ii. Feedbacks between energy demands of atmospheric carbon extraction (ACE), cost of ACE, and warming.

ISEEC estimates the amount of artificial extraction of CO_2 to generate the needed negative emission. Following the strategy laid out in Fuss et al[2], the model treats three separate approaches for carbon extraction: 1) extraction using land-based carbon sequestration by soil (charcoal) and afforestation; 2) extraction using mineralization, algae, and biogeochemical modification; 3) direct air capture by mechanical and chemical extraction of carbon. The growing capacity of ACE is constrained by technology development time and diffusion time, like renewable energy technology. Additional constraints on the growing capacity of ACE include the cost of extraction relative to a fraction of total GDP, which both vary with time, and the geophysical limits for storage of the extracted CO_2 in terms of annual amount and cumulative amount. In contrast to Fuss et al., Field and Mach[3] portray a more cautious approach to negative emissions technology. ISEEC explicitly accounts for the PE used for ACE and its potential offset to the net amount of carbon extraction if energy to power ACE is supplied from carbon-emitting sources[4],[5].

2. Natural system model (NSM)

NSM consists of two interacting components described next and in Table S1.

Table S1. Governing equations and parameters for the carbon-climate model used in the Natural Systems Model of ISEEC (adopted from Sanderson et al., 2017[6]). Note that CO_2 emission E(t) in the carbon cycle model is calculated from the fossil fuel energy supply $E_{11}(t)$ from the SSM (Table S2).

Climate Model	$\frac{\partial T_a(t)}{\partial t} = \frac{1}{\kappa_l}\left(5.35 * \ln\left(\frac{C_a(t)}{C_a(0)}\right) + F(t) - \lambda * T_a(t) - D_o * (T_a - T_o)\right)$ $\kappa_l = 20, \lambda = \frac{1}{0.8}, D_o = 0.4, C_a(0) = \frac{280}{\rho_a}$	(1.1)
	$\frac{\partial T_o}{\partial t}(t) = \frac{1}{\kappa_o} * D_o * (T_a - T_o)$ $\kappa_o = 20, D_o = 0.4$	(1.2)
Carbon Cycle Model	$\frac{\partial C_a(t)}{\partial t} = \frac{E(t) - (\gamma_l + \gamma_o) * \frac{\partial T_a(t)}{\partial t} * (1 + \delta T_a)}{1 + \rho_a(\beta_l)} - \beta_o(\rho_a C_a - \rho_o C_o)$ $\gamma_l = -0.13, \gamma_o = -0.2, \beta_o = 0.2, \rho_a = \frac{10^6}{1.8*10^{20}*12*10^{15}}, \rho_o = \frac{280}{100}, \delta = 1.1, \beta_l = 0.25$	(2.1)
	$\frac{\partial C_o(t)}{\partial t} = \beta_o(\rho_a C_a - \rho_o C_o) + \gamma_o * \frac{\partial T_a(t)}{\partial t} * (1 + \delta T_a) - \beta_{od}(\rho_o C_o - \rho_{od} C_{od})$ $\gamma_o = -0.2, \beta_o = 0.2, \rho_a = \frac{10^6}{1.8*10^{20}*12*10^{15}}, \rho_o = \frac{280}{100}, \beta_{od} = 0.25, \rho_{od} = \frac{280}{1000}, \delta = 1.1$	(2.2)
	$\frac{\partial C_{od}(t)}{\partial t} = \beta_{od}(\rho_o C_o - \rho_{od} C_{od})$ $\rho_o = \frac{280}{100}, \beta_{od} = 0.25, \rho_{od} = \frac{280}{1000}$	(2.3)

2.1 The coupled carbon-climate model

The CO_2 concentration is simulated with a carbon cycle model that considers land and ocean biological uptake and carbon diffusion into the surface ocean and deep ocean. The performance of this simpler carbon cycle model has been validated against observations[7] and the more comprehensive carbon cycle model (such as the one used in ref 8 and 9). The set-up of this carbon-cycle and energy balance model was detailed in ref 6 but we provide a brief overview of governing equations and their key parameters (Extended Data Table 2).

The core of the model is five differential equations about mass and energy conservation over time.

The first equation describes the evolution of the atmospheric temperature:

$$\frac{\partial T_a(t)}{\partial t} = \frac{1}{\kappa_l}\left(5.35 * \log\left(\frac{C_a(t)}{C_a(0)}\right) + F(t) - \lambda * T_a(t) - D_o * (T_a - T_o)\right) \quad (1)$$

where t is time and T_a and T_o are temperature anomalies of the atmosphere and ocean, respectively. The first part of the equation captures radiative forcing onto the surface-atmosphere system and the second part models heat transfers into the ocean.

F(t) is the sum of all non-CO_2 forcing, which includes non-CO_2 gases and aerosols (Fig. S1-1). For cooling aerosols, such as sulfate and nitrate, we assume they will be reduced in the future regardless of scenarios due to air quality concerns. For warming aerosols (black carbon, which is also co-emitted with organic carbon) and other short-lived climate pollutants (SLCP), there are three different configurations in our model:

1. partially coupled with fossil fuel. Note in most cases, this implies reduction, but if fossil fuel usage increases as in some cases, SLCP will increase. For the portion of SLCP that is not coupled with fossil fuel use, we assume it will stay high.
2. without coupling, and assuming SLCP will stay high (i.e., leveling off at the 2030s). This is the BAU in Fig. S1-1.
3. without coupling and assuming SLCP will decrease quickly. This is the full mitigation as in Fig. S1-1.

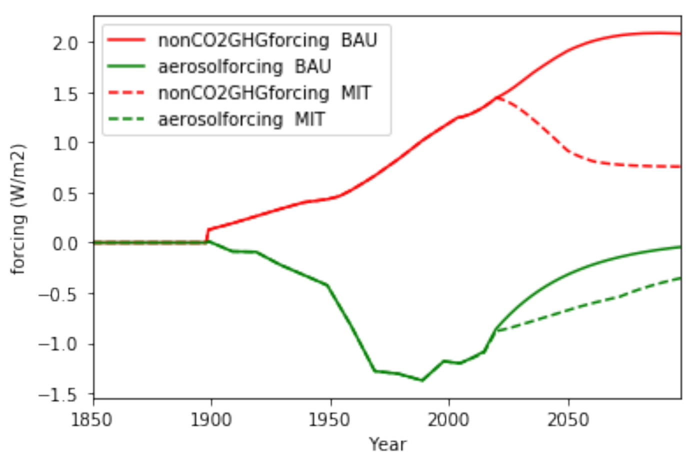

Fig. S1-1: non-CO2 radiative forcing input to ISEEC under cases where the non-CO_2 species are not coupled to fossil fuel use. "BAU" stands for business as usual or baseline. "MIT" stands for full mitigation.

λ is the climate sensitivity parameter in $Wm^{-2}K^{-1}$. Our model can also mimic the probabilistic projection due to internal variability and the uncertain range of climate sensitivity. The coupled model results (Fig. S1-2) appear to be insensitive to the noise introduced, showing numerical stability with the default time step of one year.

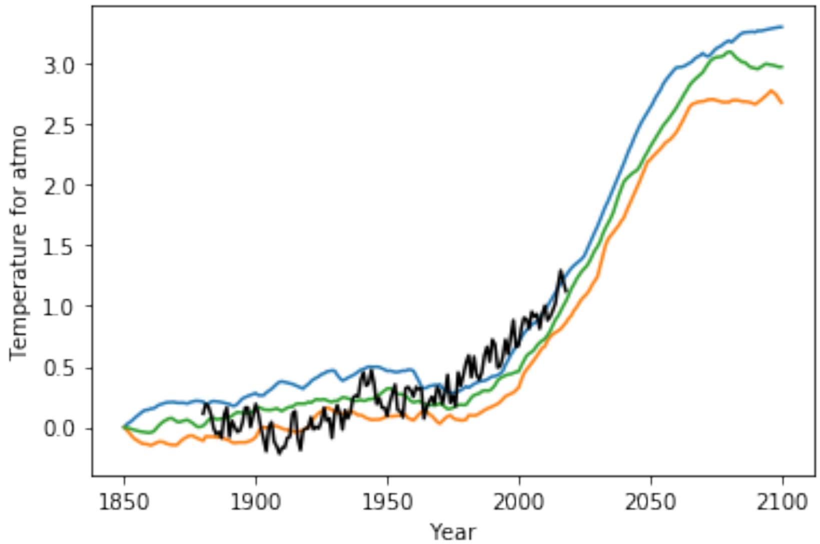

Fig. S1-2. Comparison of ISEEC simulated temperature trend with observations. Blue and orange show maximum and minimum at each time step and green show the median estimates. Observations are from GISTEMP[10].

κ_l is the thermal heat capacity of the land surface. C_a is the atmospheric carbon content in Pg. D_o is the thermal diffusion parameter between the atmosphere and the shallow ocean.

<u>The second equation</u> describes the evolution of the atmospheric carbon content (in Pg C, not in ppm):

$$\frac{\partial C_a(t)}{\partial t} = \frac{E(t) - (\gamma_l + \gamma_o) * \frac{\partial T_a(t)}{\partial t} * (1 + \delta T_a)}{1 + \rho_a * (\beta_l)} - \beta_o(\rho_a C_a - \rho_o C_o) \tag{2}$$

The first part of the equation's right side is the land surface carbon responding to emission and the second part is the carbon diffusion into the ocean. E(t) is the anthropogenic carbon emissions (which can also include negative emission sources) in Pg. γ_l and γ_o are the temperature-driven carbon feedbacks (in Pg K^{-1}) due to dissolved carbon in soil and seawater, both of which are negative values. ρ is a conversion factor from carbon content in Pg (i.e., Gt) to concentration in ppm, which has different values for the atmosphere, surface ocean, and deep ocean. β_l is the CO_2 fertilization parameter (i.e., carbon diffusion into land biosphere) and similarly, β_o is the carbon diffusion parameter from the atmosphere to the ocean.

<u>The third and fourth equations</u> describe carbon concentration in the ocean:

$$\frac{\partial C_o(t)}{\partial t} = \beta_o(\rho_a C_a - \rho_o C_o) + \gamma_o * \frac{\partial T_a(t)}{\partial t} * (1 + \delta T_a) - \beta_{od}(\rho_o C_o - \rho_{od} C_{od}) \tag{3}$$

$$\frac{\partial C_{od}(t)}{\partial t} = \beta_{od}(\rho_o C_o - \rho_{od} C_{od}) \tag{4}$$

In Eqn. 3, change in the carbon content of the shallow ocean can be due to three terms: $\beta_o(\rho_a C_a - \rho_o C_o)$ measures carbon diffusion from the atmosphere to the shallow ocean; γ_o measures ocean carbon storage sensitivity due to temperature change (both in warming rate as well as the anomaly), which is a negative value due to degassing of the warmer ocean; and $\beta_{od}(\rho_o C_o - \rho_{od} C_{od})$ measures carbon transfers into the deep ocean. In Eqn. 4, the carbon storage in the deep ocean all comes from the shallow ocean.

The last equation governs the change in ocean temperature over time:

$$\frac{\partial T_o}{\partial t}(t) = \frac{1}{\kappa_o} * D_o * (T_a - T_o) \tag{5}$$

The heat flux affecting ocean temperature comes from diffusion from the atmosphere, and κ_o is the ocean heat capacity.

Lastly, we provide a quick summary of the key parameters in this simple carbon-climate model:

- λ is the climate feedback parameter and denotes the sum of the radiation energy emitted and reflected to space per degree of warming. For λ, we adopt the value of 1.25 Wm^{-2} $^{o}C^{-1}$) which is consistent with a climate sensitivity of 4^{o}C per doubling of CO_2 concentration.
- κ is the heat capacity, the larger the κ, the longer it will take to warm.
- β is the carbon diffusion coefficient (Pg/ppm), the larger the β, the carbon transfer into ocean/land more easily given the same difference in mixing ratio.
- γ is the carbon content sensitivity to temperature rise (Pg/^{o}C).

3. Social Systems Model (SSM)

SSM consists of a set of interacting components described next. The governing equations are written down in Table S2.

Table S2. Governing equations and parameters for the Social Systems Model of ISEEC

Definitions	Equations
PE: total primary energy supply r_{EI}: a ratio representing the reduction of Energy Intensity due to climate actions GDP: global gross domestic product taken from published sources	$PE(t) = r_{EI}(T(t)) * EI(t) * GDP(t) * \sum_{i=1}^{n} \sum_{j=1}^{k} E_{ij}(t)$ with the constraint that $\sum_{i=1}^{n} \sum_{j=1}^{k} E_{ij}(t) = 1.0$; n=2 and k=4 E_{ij} Fractional contributions from the various energy sources i=1: CO_2 emitting energy sources: j=1 is fossil fuels; j=2 is traditional biomass. i=2: various renewable sources. E_{21} and E_{22} are detailed in the rows 2 and 3 below. E_{23} is traditional nuclear; and E_{24} is hydro and geothermal $r_{EI}(t) = 1$ for t<2015; and $r_{EI}(t) = e^{-0.005*T*(t-2015)}$ for t≥2015
E_{21}: Renewable Energy- Off-the-shelf technologies τ_{21}^{R}: societal response time τ_{21}^{P}: policy response time τ_{21}^{DV}: tech Development time τ_{21}^{DF}: tech Diffusion time η_{21}: startup term	$\frac{dE_{21}}{dt} = \left[1 - \frac{E_{21}(t)}{k_{21}}\right] * [\frac{E_{21}(t)}{\tau_{21}(t)}] + \eta_{21}$ $\tau_{21} = \tau_{21}^{R\to P} + \tau_{21}^{DV} + \tau_{21}^{DF}$ $\tau_{21}^{R\to P} = \max(\tau_{21}^{R}, \tau_{21}^{P})$ $\tau_{21}^{R} = \tau_{21}^{R}(0)e^{-a_1 T};\ \tau_{21}^{R}(0) = 50, a_1 = 2;$ $\tau_{21}^{P} = \frac{\tau_{21}^{R}}{2};\ \tau_{21}^{DV} = 0.0;\ \tau_{21}^{DF} = \frac{b_1}{1 + b_2 T^2};\ b_1 = 25; b_2 = 2$ $\eta_{21} = \eta_0 - \frac{E_{21}(t)}{\tau_{21}(t)}$; If $\eta_{21} < 0$; set $\eta_{21} = 0$; $\eta_0(t > 1950) = 0.1\%/\text{year}; \eta_0\ (t < 1950) = 0;$ $k_{21} = 65\%$
E_{22}: Renewable Energy- New technologies	$\frac{dE_{22}}{dt} = \left[1 - \frac{E_{22}(t)}{k_{22}(t)}\right] * [\frac{E_{22}(t)}{\tau_{22}(t)}] + \eta_{22}$ $\tau_{22} = \tau_{22}^{R\to P} + \tau_{22}^{DV} + \tau_{22}^{DF}$ $\tau_{22}^{DV} = \frac{\tau_0^{DV}}{(1+T)^{n_{22}^{DV}}}$; ($\tau_0^{DV} = 30, n_{22}^{DV} = 2$) $k_{22}(t) = 1 - E_{12}(t) - E_{21}(t) - E_{23}(t) - E_{24}(t)$ $\eta_{22} = \left\{\eta_0 - \frac{E_{22}}{\tau_{22}}\right\}$; if $\eta_{22} < 0$; set $\eta_{22} = 0.0$; $\eta_0\ (t > 2016) = 0.1\%/\text{year};\ \eta_0\ (t < 2016) = 0$
Atmospheric Carbon Extraction (details in Supplementary Information Part 1, Section 3.4) C_i: CO_2 extracted in Gt/year. C_1 denotes extraction through afforestation and enhancement of soil	$\frac{dC_i}{dt} = \varphi_i * \alpha_i * \gamma_i * (\frac{C_{i(t)}}{\tau_{i(t)}}) + \eta_i - \beta_i$ $\varphi_i = \left[1 - \frac{\Sigma_{2020}^{t_n} C_i}{K_i}\right]$; k_1 & $k_2 = 500$ Gt; $k_3 = 5000$ Gt $\alpha_i = \left[1 - \frac{C_i}{L_i}\right]$; $L_1 = L_2 = 4$ Gt CO_2/year; $L_3 = 20$ Gt CO_2/year $\gamma_1 = \gamma_2 = 1;\ \gamma_3 = 1 - \frac{Cost_3(t)}{f_{GDP}(t) * GDP(t)}$

carbon extraction; C_2 denotes extraction by mineralization and algae production in oceans; C_3 is direct air capture. φ_i: limiting factor for the cumulative extraction potential α_i: limiting factor for the annual extraction potential γ_3: limiting factor due to the cost exceeding a certain percentage of GDP η_i: initial investment to jump start the diffusion $\tau_i(t)$: the response times β_i: the release of CO_2 due to the fossil fuel related energy consumed by the carbon removal technologies e_i: energy needed to extract a unit mass of CO_2 $f_i(t)$: fossil fuel fraction of the energy used $\rho_i(t)$: carbon intensity	$\mathrm{Cost}_3(t) = C_3(t) * \mathrm{CPT}_3(t)$ CPT_3 (Cost Per Ton) = $\frac{500}{1 + 2 * C_3(t)}$; if CPT<50, set CPT=50 $f_{GDP}(t) = 0.5\% * T^2$ $\tau_i(t) = \tau_i^0 \, e^{-c_0\{T(t)-\alpha_i\}}$ $(\tau_{i=1 \text{ to } 3}^0 = 10;\ c_0 = 1; \alpha_1 = 1$ ºC; $\alpha_2 =$ 1.5 ºC; $\alpha_3 = 2$ ºC; $\eta_i = \{\eta_0 - \frac{C_i}{\tau_i}\}$; $\eta_0 =$ 0.001 Gt CO_2/year If η_i is less than zero, set it to be zero. $\beta_i = \dfrac{C_i * e_i * f_i * \rho_i}{\tau_i}$ $e_1 = e_2 = 0;\ e_3 = 10\dfrac{\mathrm{EJ}}{\mathrm{GtCO2}}$, $f_i = E_{11}(t)$ $\rho_i(t)$ decrease from 83 to 72 gCO2/MJ when T increases from 1 to 2ºC (details in Section 3.3)

3.1 PE from non-renewable and renewable sources

Non-renewable sources are fossil fuels and non-renewable biomass (e.g., deforestation and the burning of biomass for PE). Renewable sources include solar, wind, nuclear, hydrogen from solar-powered electrolysis, hydropower, and geothermal.

Let $\varepsilon_T(t)$ be the global total PE per year. We can express $\varepsilon_T(t)$ as

$$\varepsilon_T(t) = r_{EI}(t) * \varepsilon_{baseline}(t) * \sum_{i=1}^{n} \sum_{j=1}^{k} E_{ij}(\mathrm{t}) \qquad (6)$$

where $\varepsilon_{baseline}(t)$ is the baseline global PE (EJ/year), which is the major external input to the model.

For the historical period (1850-2015), we adopted $\varepsilon_{baseline}(t)$ directly from published sources[11], with the fossil fuel energy largely consistent with published CO_2 emission inventory[12]. Biomass-burning energy makes up 8% of the total in 2015. Renewable energy capacity makes up 12% of the total in 2015. Note that for the historical period, the constructed PE is the only external input to the model, while the fractional contribution of fossil fuel, biomass, and various renewable sources are all simulated by the model and are validated with the published datasets (Fig. 3 in the main text).

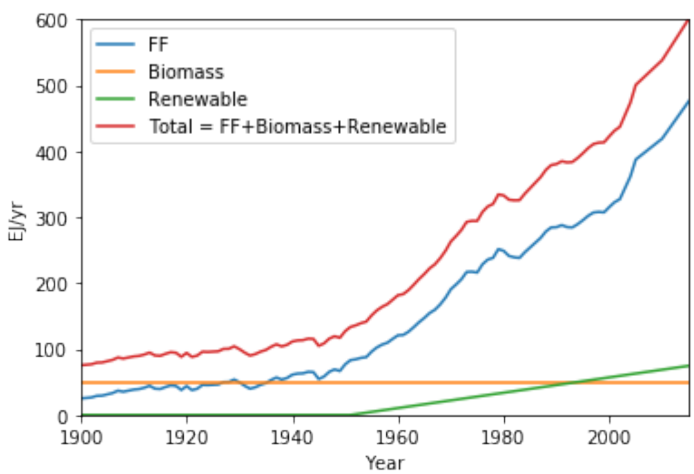

Fig. S1-3. Total PE breakdown in the simulated historical period.

For the future period (2016 - 2100), we adopted the GDP outlook[13] under a baseline scenario (SSP585; Extended Data Figure 1), which assumes a rapid economic growth with high energy demand (despite slower population growth).

The PE is then calculated by assuming a 2.5%/year reduction in energy intensity (i.e., PE/GDP) from its current value of 7 EJ/Trillion USD before 2040, and a 1.3%/year reduction in energy intensity after 2040, all consistent with SSP5 assumptions (Extended Data Figure 1b). The primary energy throughout the model simulation period (1850–2100) is shown for reference, which serves as a major input to the SSM.

$\boldsymbol{E_{ij}(t)}$ **is the *fractional* contribution to the primary energy from the various energy sources, denoted by the indices i and j.**

- Index i=1 denotes traditional energy sources (fossil fuel and biomass); and i=2 denotes non-CO_2 emitting energy sources including various renewables. CO_2 emissions can then be obtained by partitioning the fossil-fuel-related emissions (i=1) from other zero-emission clean sources (i=2).
- Index j denotes the various sectors or sub-sources (for example, wind, solar, geothermal, nuclear, hydropower, etc.) within each category of the index i.

It should be noted that, by definition,

$$\sum_{i=1}^{n}\sum_{j=1}^{k} E_{ij}\,(t) \equiv 1.0$$

so $\varepsilon_T(t) = r_{EI}(t) * \varepsilon_{baseline}(t)$ (7)

Overall, we propose that societal response to climate disruption will tend to reduce CO_2 emissions in the following ways:

1. By reducing the energy intensity of the economy *beyond* that has been assumed in the baseline, by at least another 0.5%/year. If the energy intensity further improves by the societal response to climate disruption, the ratio $r_{EI}(t)$ would become less than 1. The EI reduction can be accomplished by improving the energy efficiency of end-use, reducing waste in transmission, reducing energy demand through lifestyle change, increasing the contribution of the shared economy, among other options. We cap the maximum reduction at 30% off the baseline EI, which is typically reached in the mid-21st century in our cases (see the difference between gross energy (GE) and adjusted GE in Fig. 4).
2. By reducing the carbon intensity of fossil fuel-based PE from 83 to 72 Gt CO_2/EJ throughout global warming transition from 1ºC to 2ºC. The potential reduction of the carbon intensity of fossil fuel energy can be accomplished by fuel switching from coal to gasoline and natural gas, among other options[14].
3. While (1) and (2) above will reduce emissions from fossil fuels, the effects are rather limited (15% to 30% cut off the baseline emission). The more fundamental way of decarbonization is by replacing fossil fuel energy sources (E_{11} term) with carbon-free sources (various E_2 terms)[15]. Next, we formulate the evolving capacity of renewables by coupling the growth rates of various clean energy sources with the societal responses to climate risks. These formulations are explained in detail in the following sub-sections.

3.1.1 CO_2 emitting sources: i = 1; j = 1 to 2

j = 1 denotes the fossil fuel source, such as gas, oil, and coal.

j = 2 denotes other traditional sources of PE, such as traditional biofuel (e.g., firewood burning) and biomass burning power supply.

Note again, in Eqn. 1, $E_{11}(t)$ is fossil fuel PE in *relative* terms, not absolute values. From Eqn. 1, the PE due to CO_2-emitting sources is expressed as:

$$E_{11}(t) + E_{12}(t) = 1 - \sum_{i=2}^{n} \sum_{j=1}^{k} E_{ij}(t) \quad (8)$$

where the left side is the fractional PE due to CO_2 emitting sources and the right side is the difference between primary energy and PE from clean sources. Note that the total share of primary energy is 1.0 since all the $E_{ij}(t)$ terms make up the primary energy, $\varepsilon_T(t)$. For example, in order to reach zero carbon emissions (gross zero, not net-zero due to negative emission technology), the right side must be zero. That is, all PE is from renewable sources, which do not emit CO_2.

We use a few governing equations (see descriptions later) in ISEEC to simulate the historical and future evolution of E_{11}, formulated as a societal response to climate change. The historical and recent changes can be cross-validated with various published data sets (Fig. 2a in the main text). The fossil fuel CO_2 emissions will then be estimated from $E_{11}(t)$, using carbon intensity (CO_2 emission per fossil fuel-based PE) that gradually decreases with time. We then validate the simulated CO_2 emission from E_{11} by comparing it with CO_2 emission from the Global Carbon Budget (up to 2019). Simulated CO_2 emissions are within 10% of published values (Fig. 2b in the main text).

Note that $E_{12}(t)$ is the fractional PE from non-fossil fuel sources (e.g., traditional biomass burning for cooking, lighting, and heating by the world's poorest population). The projected values do not change much in the SSP5 future (yellow line of Fig. S1-4). Therefore, the absolute value, i.e., $\varepsilon_T(t) * E_{12}(t)$, in 2016 is held constant through 2100.

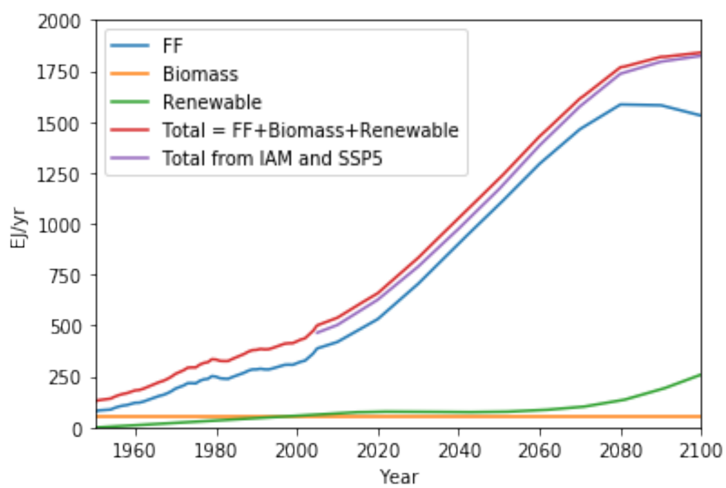

Fig. S1-4. Breakdown of total PE. Same as Fig. S1-3, but also including future period following SSP5-8.5.

Thus, for years beyond 2016, $E_{12}(t)$, defined as the faction of total, will actually decrease, because of the increase in primary energy:

$$E_{12}(t > 2016) = \frac{\varepsilon_T(2016)*E_{12}(2016)}{\varepsilon_T(t>2016)} \quad (9)$$

Note that the emission-related to the E_{12} category has been included in Global Carbon Project as falling under the land use (LU) category, which also implicitly includes the reduction of carbon sink due to deforestation and land clearance. Thus, we directly prescribe the LU emission from published sources (Global Carbon Project before 2019[16] and SSP5-RCP8.5 after 2019[17]), without explicitly simulating LU-related CO_2 emission, which is a subject of previous studies coupling climate and land use in the future[18].

In summary, the anthropogenic CO_2 emission that leads to concentration increase is from sources of fossil fuel (simulated E_{11} term) and land use (prescribed). The main contribution of ISEEC is to make E_{11} (via various E_{2j} terms, defined in the next section) dependent on societal response to climate change. While E_{12} is included in the PE but not explicitly accounted for in the carbon emission budget, it does not affect our findings since this study focuses on future climate mitigation by reducing fossil fuels.

3.1.2 Renewable Sources: i = 2; j =1 to 4

We consider the following categories of carbon-free energy sources:

- E_{21} is renewable energy using off-the-shelf technology, such as photovoltaics; wind; biofuels. No development is needed for this category.
- E_{22} is renewable energy using emerging new technology, such as hydrogen from electrolysis, reusable batteries, safe nuclear, micro-, and nano- grids. E_{22} is approximately zero as of 2016.
- E_{23} is traditional nuclear.
- E_{24} is traditional renewable energy, such as geothermal and hydropower, which are subject to geophysical limitations.

From REN (2019) report[19], for the year 2016, which is the start year of our "future" simulation:

- E_{11} = 79%
- E_{12} = 8% (traditional non-renewable biomass)
- E_{21} = 2.6% (e.g., solar and wind)
- E_{23} = 2.2% (e.g., nuclear)
- E_{24} = 7.8% from geothermal (4.1%) and hydropower (3.7%)

Thus, we deduce that E_{22} is negligible, but we assume it to be 0.4% for emerging renewable technologies (calculated as a residual of $1-E_{11}-E_{12}-E_{21}-E_{23}-E_{24}$) as of 2016, which provides the initial condition for E_{22} in the simulations.

Note that for the terms above, E_{21} (solar and wind) is the only one that will be simulated for a historical period (up to 2015), while E_{22}, E_{23}, and E_{24} are prescribed up to 2015 based on the reported present-day capacity (assuming linear growth starting from 2010, 1970, 1950, respectively). Thus, we first describe the treatment of the E_{21} term in detail below.

3.1.2.1 E21: Renewable Sources Using Current Technologies

We develop the equation for the first renewable term: E_{21} (renewable using current technology, such as solar and wind).

$$\frac{\mathrm{dE_{21}}}{\mathrm{dt}} = \text{ Startup } + \text{ Diffusion, in which} \tag{10}$$

$$\text{Startup: } \eta_{21} = \{\eta_0 - \frac{\mathrm{E_{21(t)}}}{\tau_{21(t)}}\};\ \text{if } \eta_{21} < 0;\ set\ \eta_{21} = 0$$

$$\text{Diffusion} = \left[1 - \frac{\mathrm{E_{21\,(t)}}}{\mathrm{k_{21}}}\right] * [\frac{\mathrm{E_{21(t)}}}{\tau_{21(t)}}]$$

τ_{21} is effective Response Time in years.

$$\tau_{21} = \tau_{21}^{R\to P} + \tau_{21}^{DV} + \tau_{21}^{DF} \tag{11}$$

in which

$\tau_{21}^{R\to P}$: the combined response to societal response and policy response

τ_{21}^{R}: societal response time

τ_{21}^{P}: policy response time

τ_{21}^{DV}: technology development time

τ_{21}^{DF}: technology diffusion time

For the standard model, we assume that it is the larger of the two response times, that is $\max(\tau_{21}^{\mathrm{R}}, \tau_{21}^{\mathrm{P}})$. For an upper range of response time, we assume $\tau_{21}^{R\to P} = \tau_{21}^{\mathrm{R}} + \tau_{21}^{\mathrm{P}}$.

Each of the response times is expressed as a function of warming as follows

$$\tau_{21}^{\mathrm{R}} = \tau_{21}^{\mathrm{R}}(0)\, e^{-a_1 T} \tag{12}$$

In which, $\tau_{21}^{\mathrm{R}}(0) = 50$, $a_1 = 2.0$

$$\tau_{21}^{\mathrm{P}} = \frac{\tau_{21}^{\mathrm{R}}}{a_2}, \qquad \text{in which, } a_2 = 2.0 \tag{13}$$

$\tau_{21}^{DV} = 0.0$ because E_{21}-related renewable technology is already developed as of 2016.

$$\tau_{21}^{DF} = \frac{b_1}{1 + b_2 T^2} \tag{14}$$

$$\text{in which, } b_1 = 25, b_2 = 2 \tag{15}$$

The $\frac{E_{21}}{k_{21}}$ term within the square bracket limits the growth of E_{21} fraction to the total energy. This can come from limitations of land area, battery waste, etc.

We set k_{21}= 0.65 (16)

That is, conventional solar and wind can only meet 65% of the primary energy at maximum.

In summary, with Eqn. 10, we can integrate $\varepsilon_T(t) * E_{21}$ from 0 in the year 1850, continually through 2100, thus achieving the full coupling of energy-emission-climate. The startup term, η_{21}, is the initial capacity building or investment needed to prime (jump-start) the diffusion. Initially, E_{21} is zero and as can be inferred from Eqns. 3 to 5, $\frac{dE_{21}}{dt}$ is determined by η_0, which is set to 0.1%/year. The diffusion term allows for the diffusion of technology, past the initial stage, to its full potential, which is determined by k_{21}. The variable k_{21} is the upper limit (the full potential) for the percentage of PE that can be provided by E_{21}.

3.1.2.2 E_{22}: Renewable Using New Technology

$$\frac{dE_{22}}{dt} = \left[1 - \frac{E_{22\,(t)}}{k_{22}}\right] * \left[\frac{E_{22(t)}}{\tau_{22(t)}}\right] + \eta_{22} \tag{17}$$

$$\tau_{22} = \tau_{22}^{R\to P} + \tau_{22}^{DV} + \tau_{22}^{DF} \tag{18}$$

$\tau_{21}^{R}, \tau_{21}^{P}, \tau_{21}^{DF}$ are formulated the same as those for E_{21}.

$$\tau_{22}^{DV} = \frac{\tau_0^{DV}}{(1+T)^{n_{22}^{DV}}} \tag{19}$$

$\tau_0^{DV} = 30$

$n_{22}^{DV} = 2$

If $\tau_{DV} < \tau_{DV}^{min}$; $\tau_{DV} = \tau_{DV}^{min} = 4$

$$k_{22}\,(t) = 1.0 - E_{12}\,(t) - k_{21} - E_{23}\,(t) - E_{24}\,(t) \tag{20}$$

As of 2016, E_{23} = 0.02; E_{24} = 0.08. So, with the assumed k_{21}=0.65**,** we set k_{22} = 0.25 in 2016 with the expectation it will increase in future.

$\eta_{22} = \{\eta_0 - \frac{E_{22}}{\tau_{22}}\}$ (η_0 = 0.1 %), which is akin to η_{21}.

The governing equation for E_{22} (Eqn. 17) is only used for future projection. Without the start-up term, it will take several decades for a technology to diffuse from zero to its full potential. For the historical period, since E_{22} = 0.4% in 2016, we assume that $\varepsilon_T(t) * E_{22}$ increases linearly from 0 in 2000 to its 2016 value.

3.1.2.3 E_{23}: Traditional Nuclear

For the historical period, since E_{23} = 2.2% in 2016, we assume that $\varepsilon_T(t) * E_{23}$ increases linearly from 0 in 1970 to its 2016 value. For the future, we keep the PE in absolute value (not the fraction) the same as 2016. As a result, E_{23}, defined below as a fraction, will gradually decrease.

$$E_{23}(t>2016) = \frac{\varepsilon_T(t) *(2016)*E_{23}(2016)}{\varepsilon(t>2016)} \tag{21}$$

3.1.2.4 E_{24}: Traditional Renewable Sources (geothermal, hydropower)

For the historical period, since E_{24} =7.8% in 2016, we assume $\varepsilon_T(t) * E_{24}$ increases linearly from 0 in 1950 to its 2016 value. For the future, we keep the PE in absolute value (not the fraction) the same as 2016. So E_{24}, defined below as a fraction, will gradually decrease.

$$E_{24}(t>2016) = \frac{\varepsilon_T(t) *(2016)*E_{24}(2016)}{\varepsilon(t>2016)} \tag{22}$$

3.2 Mitigation due to Improvements in Energy Intensity

The baseline primary energy, $\varepsilon_{baseline}(t)$, assumes implicitly a marginal 1.3-2.5% per year decrease in energy intensity. However, previous studies[20] suggest a further decrease of up to 1.4% per year in energy intensity is possible[21].

$r_{EI}(t)$ represents the *ratio* of the energy intensity (EI, primary energy per GDP, in the unit of EJ/TrillionUSD) between the actual world and the baseline scenario. We propose that

$$r_{EI}(t) = \frac{EI(t)}{EI_{baseline}(t)} = e^{-0.005*T*(t-2015)} \quad \text{for } t \geq 2015 \tag{23}$$

With the constraint that $r_{EI} > 0.7$ (24)

The temperature parameterization assumes that as the planet warms there will be more incentive to achieve a stronger reduction in energy intensity and the percent reduction is 0.5-2.0% per year, in addition to the assumed reduction in energy intensity in the $EI_{baseline}(t)$. However, we limited the maximum feasible reduction in intensity to be 30%, which is typically reached around 2050 in our base case, and it effectively translates to an *additional* 1.1%/year decrease during 2016 and 2050.

3.3 Mitigation due to Improvements in Carbon Intensity

Once we determine the primary PE from fossil fuels (E_{11} term), we use a carbon intensity factor to convert it to CO_2 emissions. This factor can be estimated from the published CO_2 emission and energy data and is dependent on the apportionment of fossil fuels between coal, oil, and natural gas. For example, switching from coal to oil and natural gas in the next few decades over part of the globe will reduce the carbon intensity. To factor this in without simulating the detailed makeup of fossil fuel, we propose that there will be a switch from coal to gasoline and gas when the warming exceeds 1.5ºC. We mimic this transition by formulizing the following:

When T is less than 1ºC, we adopt the carbon intensity of 83 gCO_2/MJ due to the current use of coal/gasoline/natural gas (2006-2015). When T is greater than 2ºC, coal will be completely phased out, and we adopt a lower carbon intensity of 72 gCO_2/MJ. We assume a linear reduction of emission factor (i.e., carbon intensity) when T increases from 1 to 2 ºC.

3.4 Atmospheric Carbon Extraction (ACE)

Let CO_2 extraction be denoted by C_i, typically shown in the unit of Gt CO_2 per year. We want to develop an equation for CO_2 reduction due to various ACE methods. The index i represents the approach of carbon extraction:

- i=1 denotes extraction using soil improvement, afforestation, and other land-based natural solutions.
- i=2 denotes mineralization, algae, and biogeochemical modification.
- i=3 denotes the mechanical-chemical extraction of carbon dioxide (i.e., direct air capture).

We make a clear distinction between gross extraction and net extraction, with the difference being emissions due to energy demand for powering ACE.

$$\frac{dGrossC_i}{dt} = \varphi_i * \alpha_i * \gamma_i * \frac{GrossC_{i(t)}}{\tau_i(t)} + \eta_\iota \quad \text{for t>2016 only.} \tag{25}$$

$$\frac{dNetC_i}{dt} = \frac{dGrossC_i}{dt} - \beta_i \qquad \text{for t>2016 only.}$$

The first term on the right side is the limiting factor for the cumulative extraction potential and is defined as:

$$\varphi_i = \left[1 - \frac{\sum_{2016}^{t_n} \Delta t * NetC_i}{k_i}\right] \tag{26}$$

$\sum_{2016}^{t_n} \Delta t * C_i\,(t)$ is the cumulative net extraction from 2016 to a future year, t_n. Δt is the time step (1 year) such that the cumulative sum of the product is Gt CO_2 removed.

The rate-limiting factors, k_i, are:

$k_1 = k_2 = 500$ Gt CO_2. (27)

$k_3 = 5000$ Gt CO_2.

While k_3 makes an almost limitless potential for i=3, the chemical and mechanical extraction is limited by annual extraction potential. This is treated in the second term α_i, a limiting factor defined as:

$$\alpha_i = \left[1 - \frac{NetC_i}{L_i}\right]$$

The rate-limiting factors of L_i are:

$L_1 = L_2 = 4$ Gt CO_2/year. (28)

$L_3 = 20$ Gt CO_2/year

The third term is the economic limiting factor due to the ACE cost exceeding a certain percentage of global GDP. It is formulated as:

$\gamma_i = 1$ for i=1 and 2.

$$\gamma_3 = 1 - \frac{Cost_3\,(t)}{f_{GDP}(t) * GDP(t)} \quad (29)$$

where $Cost_3$ is estimated as:

$$Cost_3 = NetC_3(t) * CPT_3\,(t) \quad (30)$$

where CPT_3 is the Cost Per Ton of CO_2. Smith et al.[22] estimated a range of \$1,650 to \$2,100 per ton of carbon, which translates to a CPT_3 of \$435 to \$572. We assume the central value of \$500 for CPT_3 in 2020, which would decrease in time because of the scale of the economy. We model it by letting:

$CPT_3\,(t) = \frac{500}{1 + 2 * NetC_3(t)}$; where $NetC_3$ is in the unit of Gt CO_2/year

if $CPT_3 < \$50$, we set $CPT_3 = \$50$.

$$f_{GDP}\,(t) = 0.5\% * T^2 \quad (31)$$

GDP(t) is the GDP data obtained from SSP5, the highest growth among the five scenarios, for which we fit with an exponential function.

The expression for f_{GDP} (t) implies that societies' willingness to pay will depend on the magnitude of the warming. For example, when the warming reaches 1ºC, the society will be willing to pay a maximum of 0.5% of the GDP; when the warming reaches 2ºC, the society may be willing to pay 2% of GDP. In our base case, the ACE_3 cost amounts to 1.3% of GDP at most.

Our estimate of the cost is conservative. For example, we are ignoring the additional cost and energy incurred for storing the extracted CO_2. For ACE_3, we need to store the extracted CO_2 in deep geological spaces (e.g., regions where fossil fuels were extracted). To give a perspective on the magnitude of 600 billion tons, which is the estimated amount of CO_2 that would need to be stored from the fully coupled ISEEC (Fig. S1-1), the annual solid waste supply by the world is 2 billion tons, so we would need to create enough space to store 300 years' worth of solid waste. Therefore, in the sub-model, the ACE_3 capacity is also capped based on assumed geophysical limits for storage of the extracted CO_2 in terms of annual amount and cumulative amount.

We set $NetC_{i=1,2,3}$ (2016) = 0.0 Gt/year, which will make it as an initial value problem. To avoid that, similar to the E_{21} formulation, we introduce a η_i term:

$$\eta_i = \eta_0 - \frac{GrossC_i}{\tau_i} \tag{32}$$

We set $\eta_0 =$ 0.001, but also tested 0.01 and 0.05

Note that if $\eta_i < 0, we\ set\ \eta_i = 0$ (33)

The last term on the right side is CO_2 emission due to fossil fuel use by carbon removal technologies. It is expressed as:

$$\beta_i = \frac{GrossC_i * e_i * f_i * \rho_i}{\tau_i} \tag{34}$$

Where, e_i is energy per ton of CO_2 extracted (in gross term).

For i=1 & i=2, we ignore the emission by setting e_i =0.0, and thus $\beta_i = 0$ (35)

For i=3, Keith et al.[23] gives 8.81 GJ (using natural gas) per ton of gross extracted CO_2. A literature review by Smith et al.[22] gives 45 GJ per ton of carbon, which translates to 12.25 GJ/ton of CO_2.

Therefore, here we adopt the estimates that

e_3 =10 GJ/ton of CO_2 = 10 EJ/Gt of gross CO_2 extraction

Note that 1 exa (10^{18}) = 1 giga (10^9) *1 giga (10^9).

Thus, a capped 20 Gt CO_2 extracted (in gross term) in 2100 in our base case would require 200 EJ per year, consisting of a major component of the energy landscape. For context, global PE in 2013 is about 567 EJ/year.

Next, $f_i(t)$ = fossil fuel fraction of the PE = $E_{11}(t)$ (36)

And $\rho_i(t)$ is the carbon intensity which can vary in time.

Lastly, we formulate the response times required in Eqn. 25:

$$\tau_i(t) = \tau_i^0 * e^{-C_0[T(t)-\alpha_i]} \quad ; \qquad if\ \tau_i(t) < 1\ year, set\ \tau_i(t) = 1\ year \tag{37}$$

The constants in Eqn. 37 are set as:

$C_0 = 1\ year^{-1}$ (38)

τ_1^0=10 years; α_1 = 1 ºC (39)

τ_2^0 = 10 years; α_2 = 1.5 ºC (40)

τ_3^0 = 10 years; α_3 = 2 ºC (41)

Part 2

Sensitivity studies conducted with ISEEC

including 1 Supporting Table and 12 Supporting Figures

Table S3. Sensitivity studies for Energy-Climate Interactions. R_1.5C is Share of Renewable at 1.5ºC warming. The fully coupled version of ISEEC includes the following: warming-dependent response times; mitigation of SLCPs and aerosols emitted by fossil fuels; Atmospheric Carbon Extraction driven by warming. The three entries under the second column (“CO_2 Net Emission”) are peak emission amount (and year of peaking); year of reaching net-zero emission; and cumulative net emission (from 2015 to 2100).

Case Number and Case Name	CO_2 Net Emission	Peak CO_2 Concentration (Year)	Peak Warming (Year)	2100 Warming	R_1.5C and ACE (from 2015 to 2100)	Details
1. ISEEC-Fully Coupled	42 Gt (2025); 2058; 350 Gt	435 ppm (2047)	2.3ºC (2075)	2.2ºC	20% 1100 Gt	Base model with all the energy-climate interactions. Fig. S2-1.
1.b ISEEC-Fully Coupled	42 Gt (2025); 2058; 300 Gt	430 ppm (2045)	2.2ºC (2075)	2.1ºC	20% 1050 Gt	Base model but a smaller b_1 of 20 years. Fig. S2-11.
2.a ISEEC-Partially Decoupled	42 Gt (2030); n/a; 2460 Gt	480 ppm (2040)	>3.5ºC (>2100)	3.5ºC	13% 1050 Gt	Same as 1, but without warming dependent response times; fixed at 2015 values. Fig. S2-2.
2.b ISEEC-Fully Decoupled	60 Gt (2050); n/a; 4050 Gt	590 ppm (2100)	>4.6ºC (>2100)	4.6ºC	11% 1050 Gt	Same as 2.a, but also without warming dependent energy intensity, fixed at 1.0. Fig. S2-10.
3. Case 1 with faster response times	42 Gt (2021); 2050; 60 Gt	425 ppm (2040)	2.1ºC (2075)	2ºC	45% 1000 Gt	Beginning 2016, response times were estimated using projected warming 20 years into the future. Fig. S2-3.

4. Case 1 with a boost in initial investment	41 Gt (2020); 2045; -100 Gt	415 ppm (2038)	2.0ºC (2090)	1.9ºC	55% 850 Gt	Beginning 2016, increase start-up investment from 0.1%/year to 2%/year. Fig. S2-4 and Fig. S2-5.
5. Cases 3+ 4 + mitigation of all SLCPs	41 Gt (2020); 2038; -25 Gt	415 ppm (2029)	1.6ºC (2040)	1.4ºC	70% 700 Gt	Mitigation of non-fossil fuel SLCPs, in addition to fossil fuel. Fig. S2-6.
6. Case 1+ without ACE	45 Gt (2030) 2100; 1420 Gt	440 ppm (2045)	2.5ºC (2100)	2.5ºC	22% 0 Gt	Fig. S2-7.
7. Case 6+ without fossil fuel related SLCP mitigation.	45 Gt (2030) 2100; 1390 Gt	440 ppm (2045)	3.1ºC (2100)	3.1ºC	22% 0 Gt	Fig. S2-8.
8. Case 6+ without improvement of energy intensity	50 Gt (2030) 2100; 1770 Gt	460 ppm (2050)	2.7ºC (2100)	2.7ºC	22% 0 Gt	Energy intensity ratio set to 1.0. Fig. S2-9.
9. Case 1 + mitigation of all SLCPs	42 Gt (2021); 2068; 1040 Gt	450 ppm (2050)	1.8ºC (2050)	1.8ºC	45% 800 Gt	Mitigation of non-fossil fuel SLCPs, in addition to fossil fuel. Fig. S2-12.

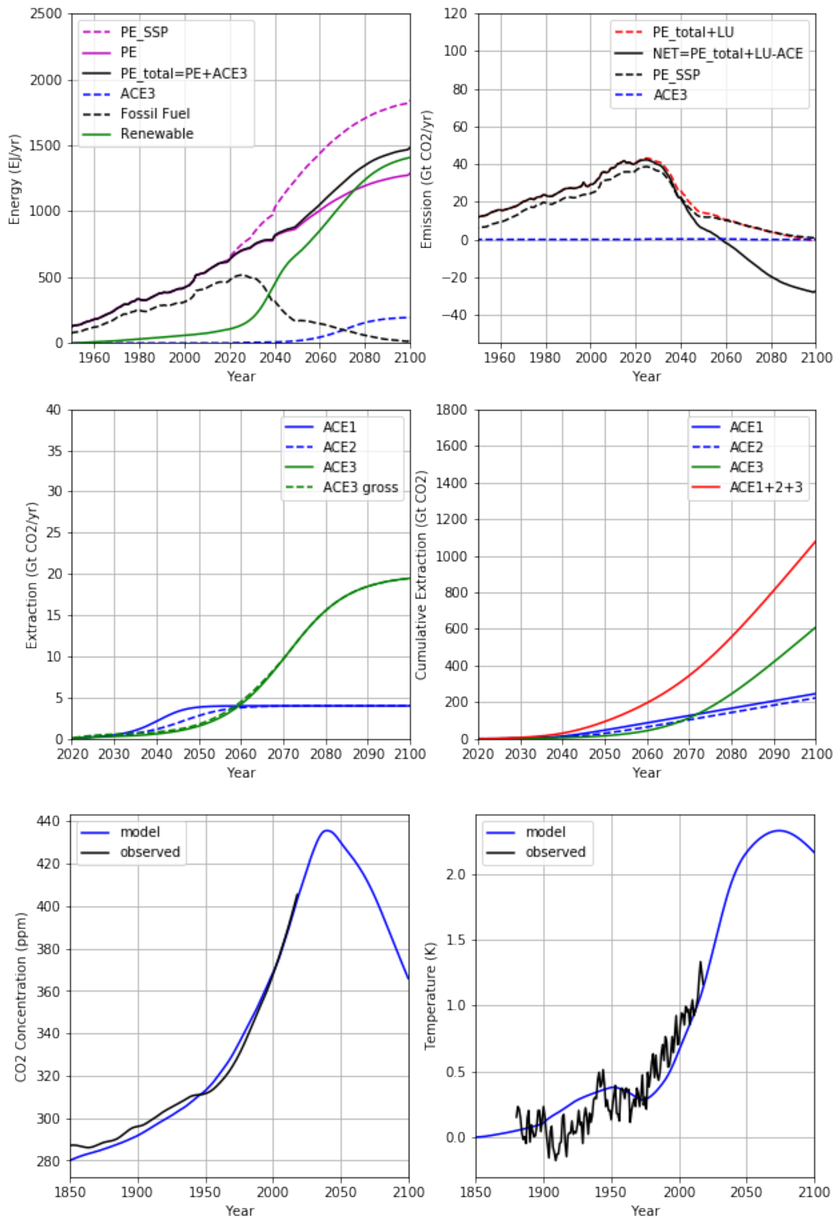

Fig. S2-1. The base version of ISEEC (fully coupled). All response times are temperature dependent. SLCP mitigation is coupled with fossil fuel use. Same as in Fig. 4 top panels.

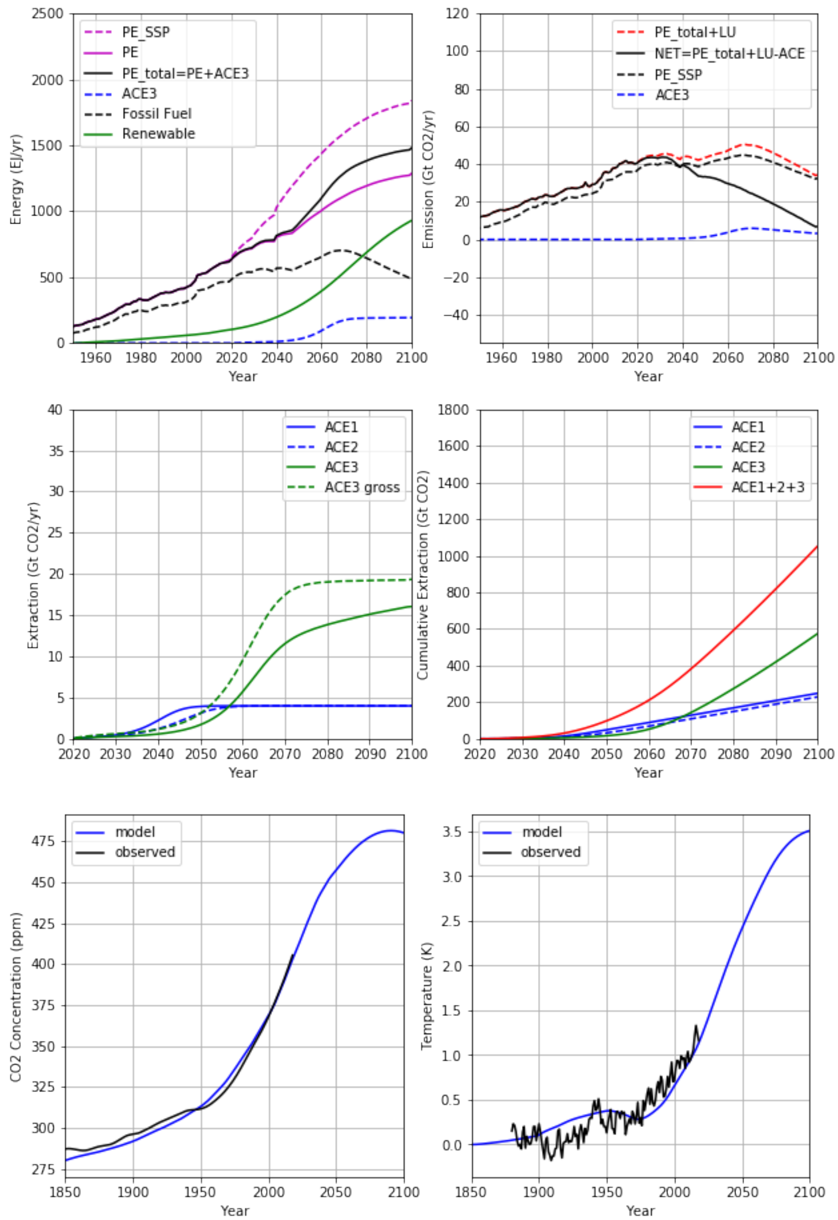

Fig. S2-2. ISEEC Partially Decoupled. That is, the response times are fixed at their 2015 levels. ACE3 in the top-right panel of "Emission" is the ACE3-related emission, which would offset the gross extraction amount (dashed green line in "Extraction" panel) thus the net ACE3 extraction (solid green in "Extraction" panel) is smaller. "ACE3" (solid green line) in the "Cumulative Extraction" panel refers to the net amount of extraction (i.e., gross minus offset).

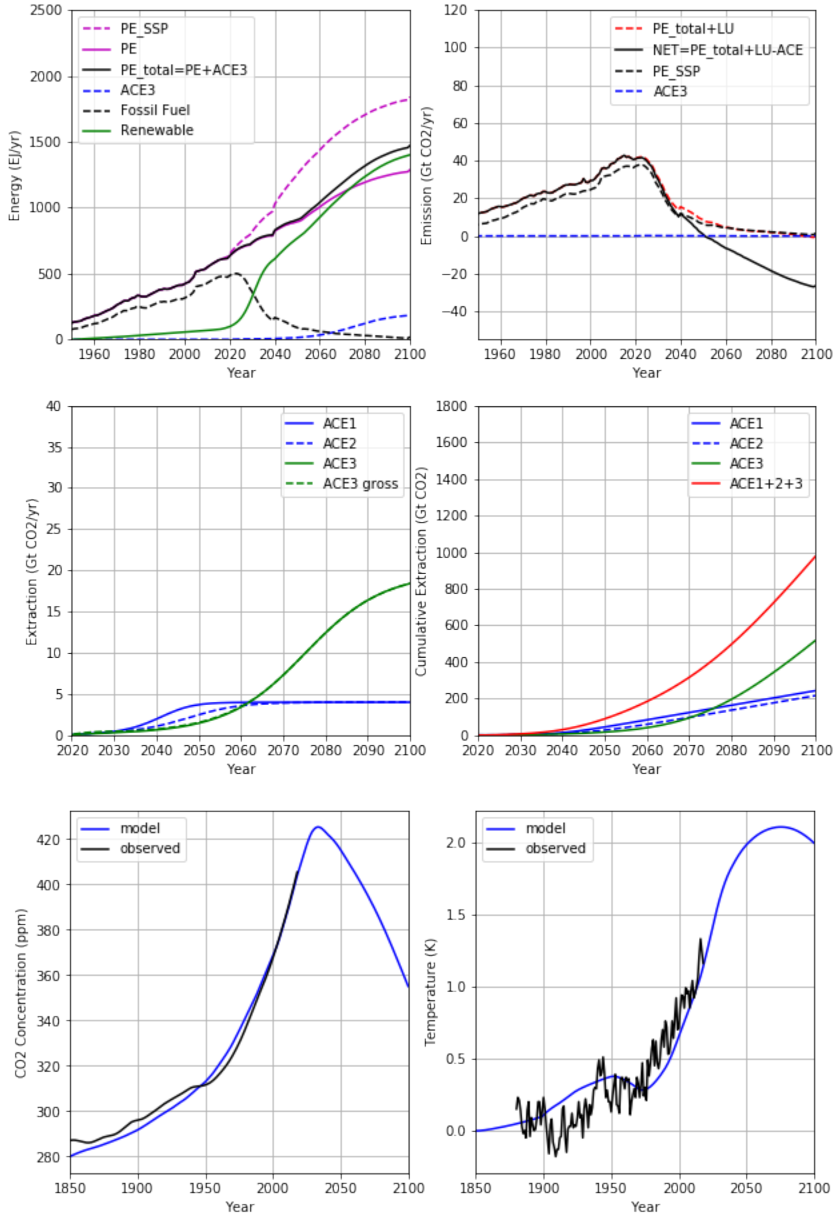

Fig. S2-3. Same as the base case, but with a quicker time constant reduction based on anticipated warming 20 years ahead (i.e., ~0.6ºC warmer). We replaced the temperature in the response time $\tau_{ij}(t)$ with T(t) = T'(t)+0.6ºC, where T(t) is the temperature inserted in the equations for τ_{ij} and T'(t) is the temperature simulated by the NSM. The addition of 0.6ºC is equivalent to the additional warming over the next 20 years because the projected warming rate is about 0.3ºC/decade.

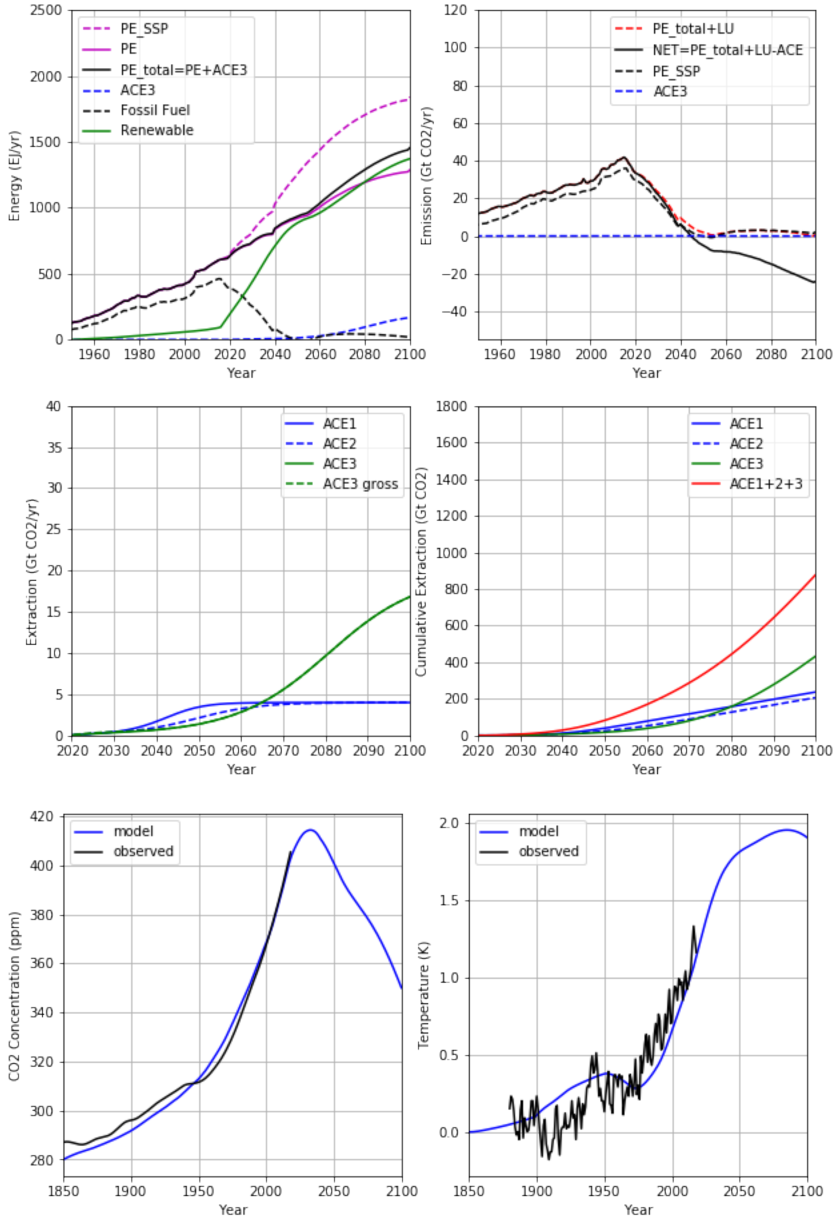

Fig. S2-4. Same as the base case, but the initial startup terms for E_{21} and E_{22} are increased to 2%/year beginning 2016.

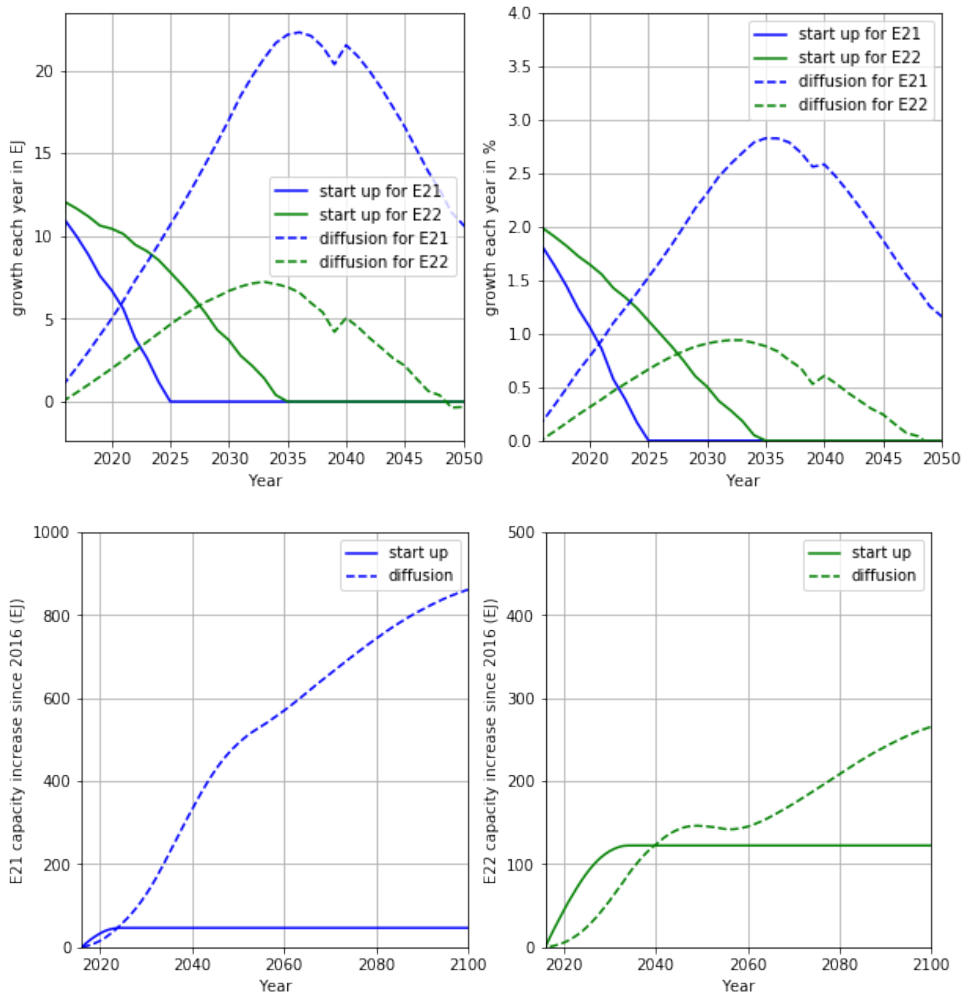

Fig. S2-5. The breakdown of start-up term and diffusion term (in Eqn. 1) as in Case 4 (Fig. S2-4): initial startup terms of 2%/year beginning 2016.

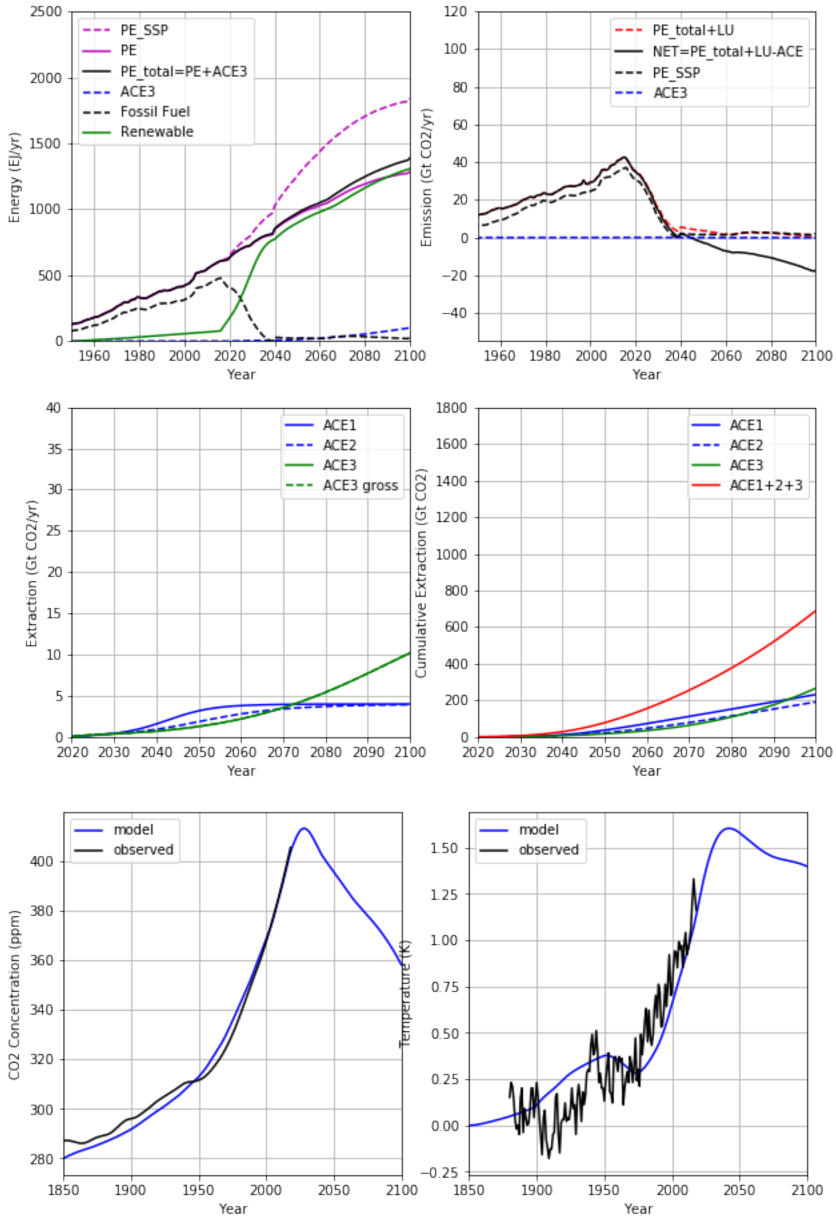

Fig. S2-6. Full SLCP mitigation, but also with faster reduction of response time due to anticipated higher warming, and a 2%/year initial start-up investment. Also shown in Fig. 5.

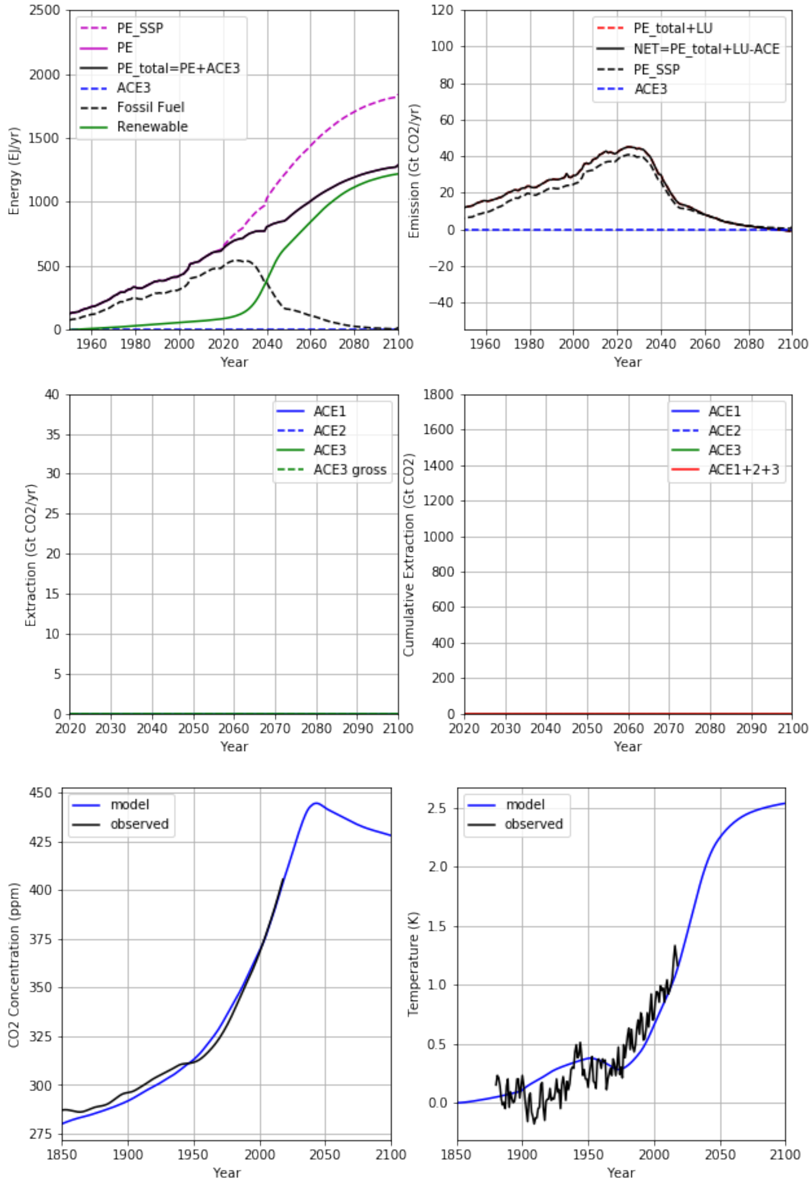

Fig. S2-7. Same as the base model but without ACE.

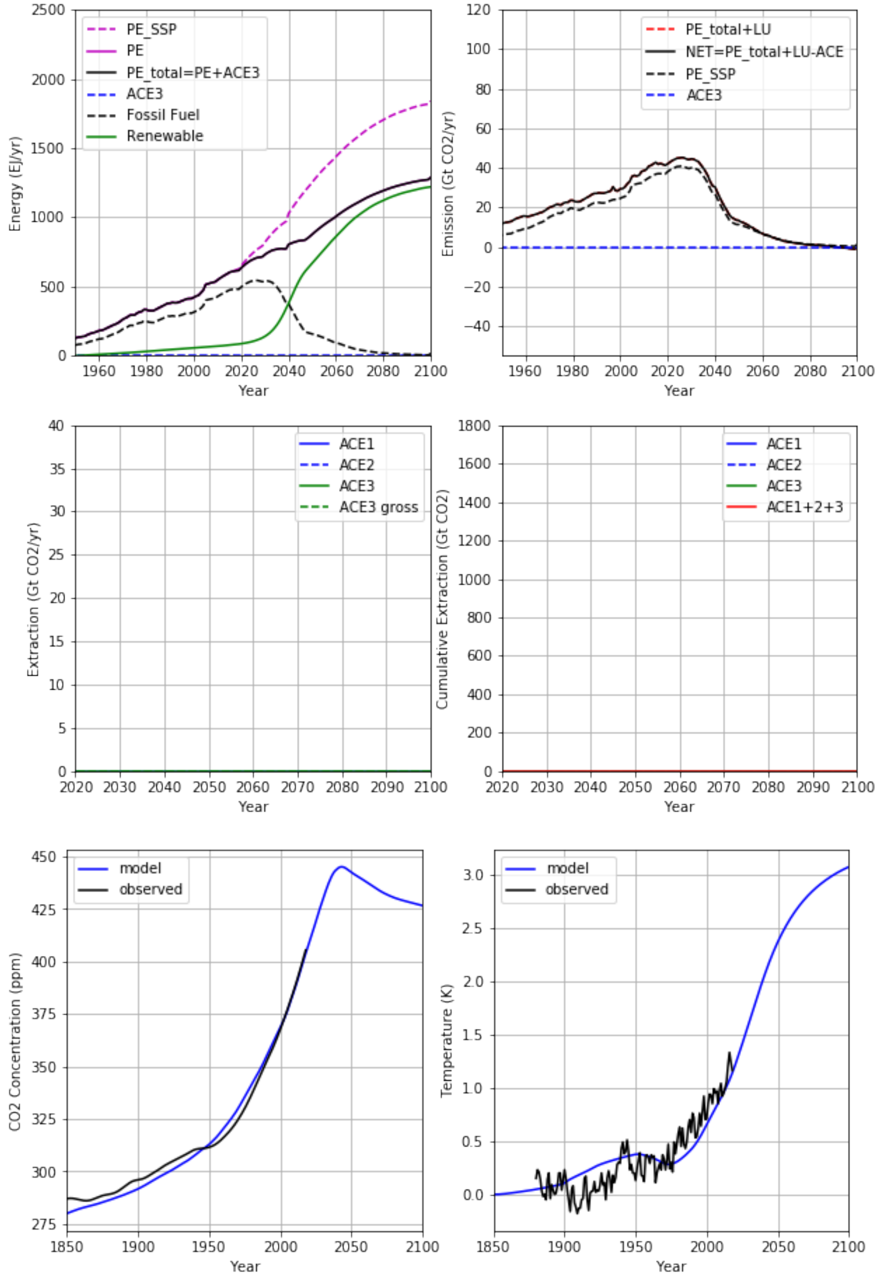

Fig. S2-8. Same as Case 6, but also without mitigating fossil fuel SLCPs.

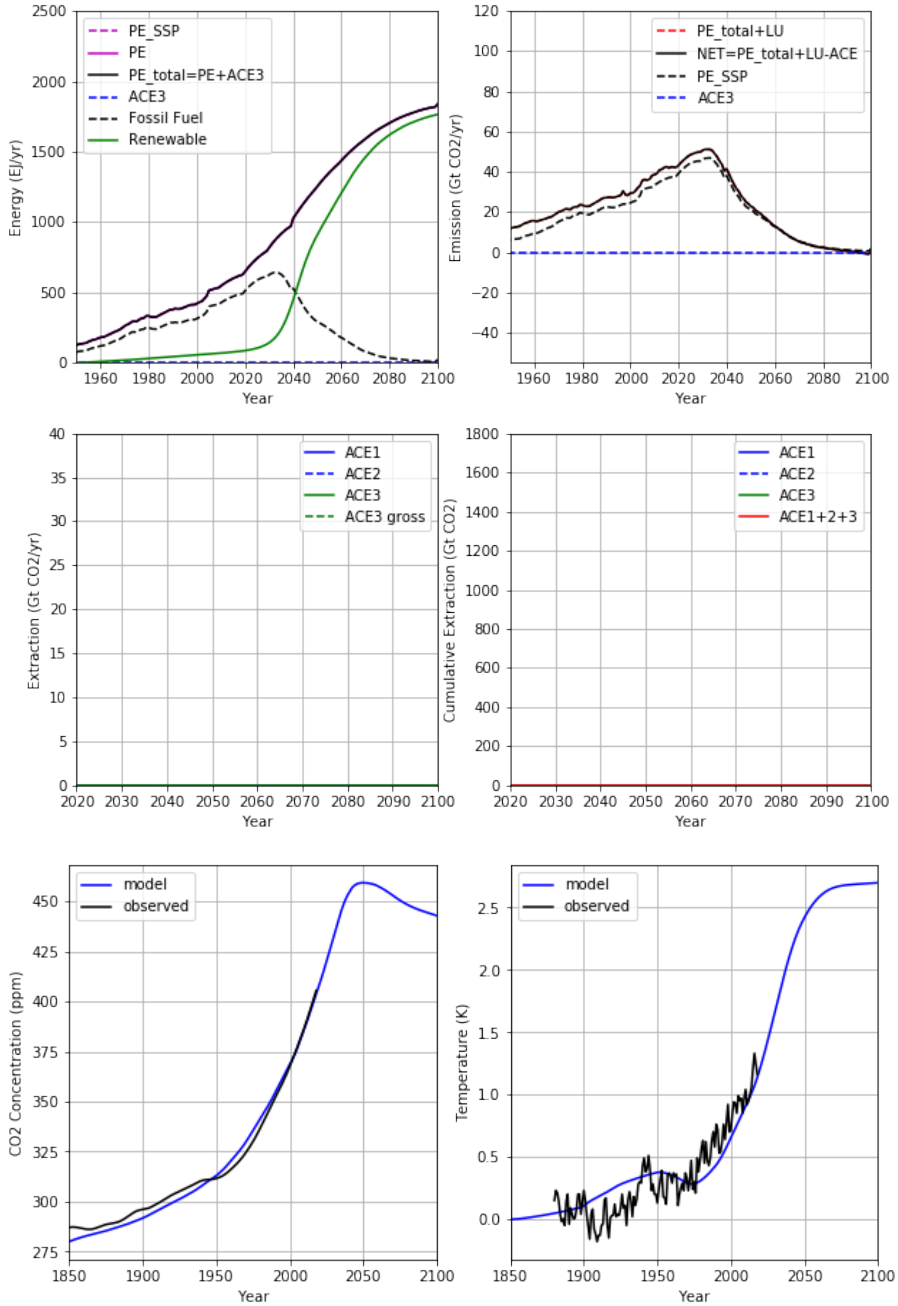

Fig. S2-9. Same as Case 6, but with the energy intensity ratio set to 1.0 throughout the 21st century.

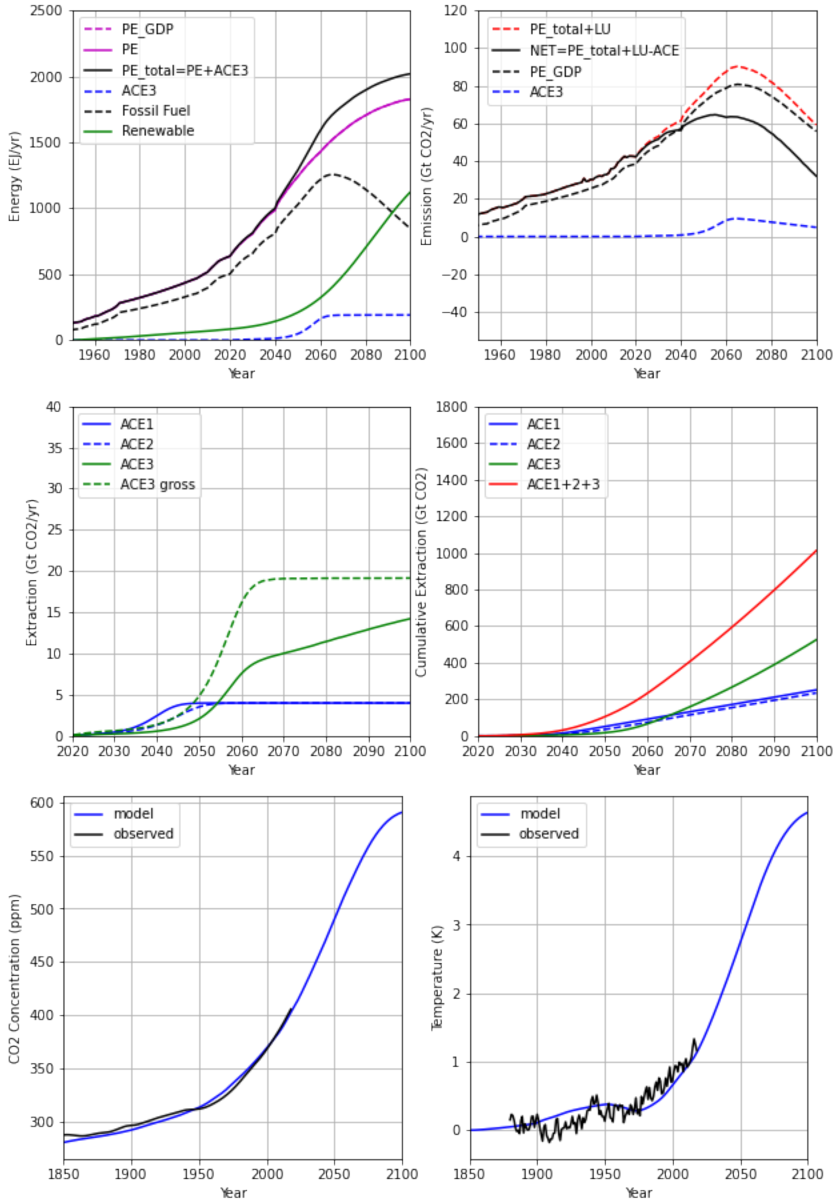

Fig. S2-10. Case 2.b, also shown in Fig. 4 bottom panels.

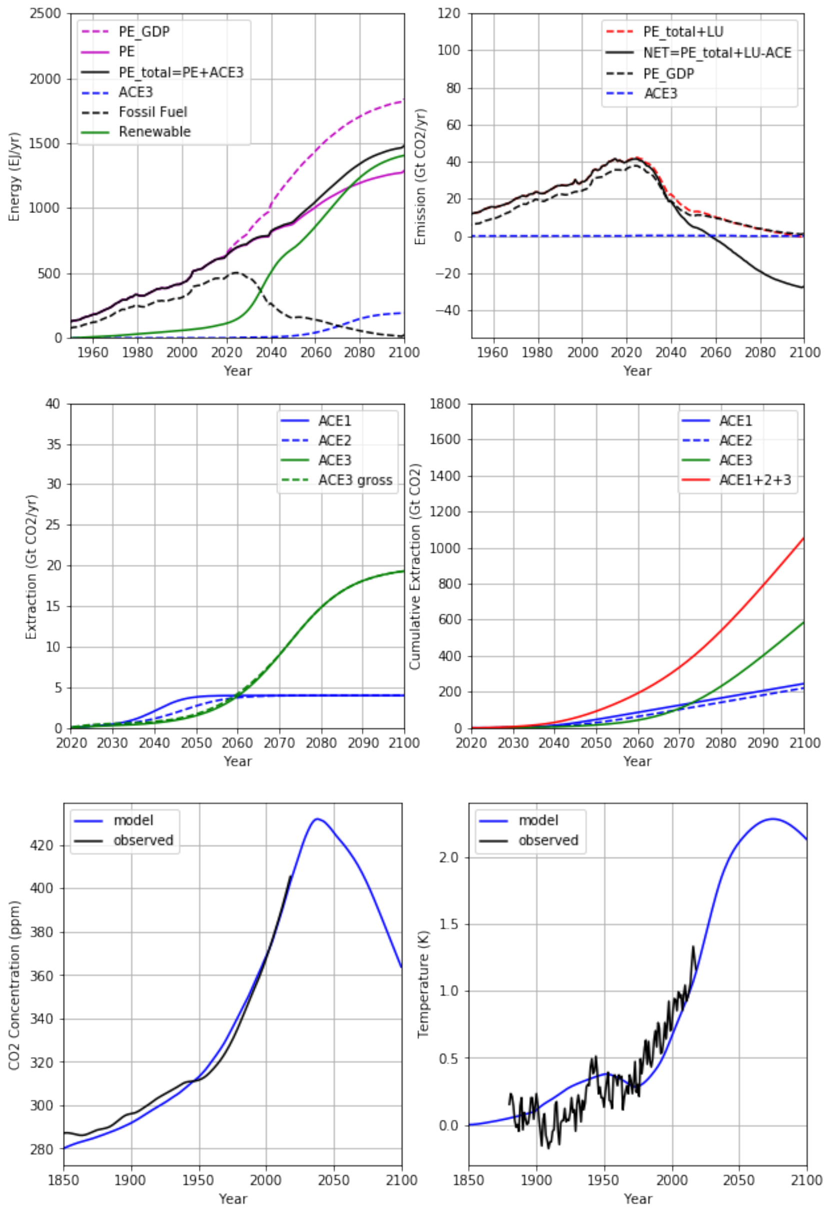

Fig. S2-11. The base case of ISEEC (fully Coupled) but with b_1=20 years as tested in Fig. S2-3b. Note that because of the smaller response time, the end of century warming is lowered by ~0.2°C to 2.1°C.

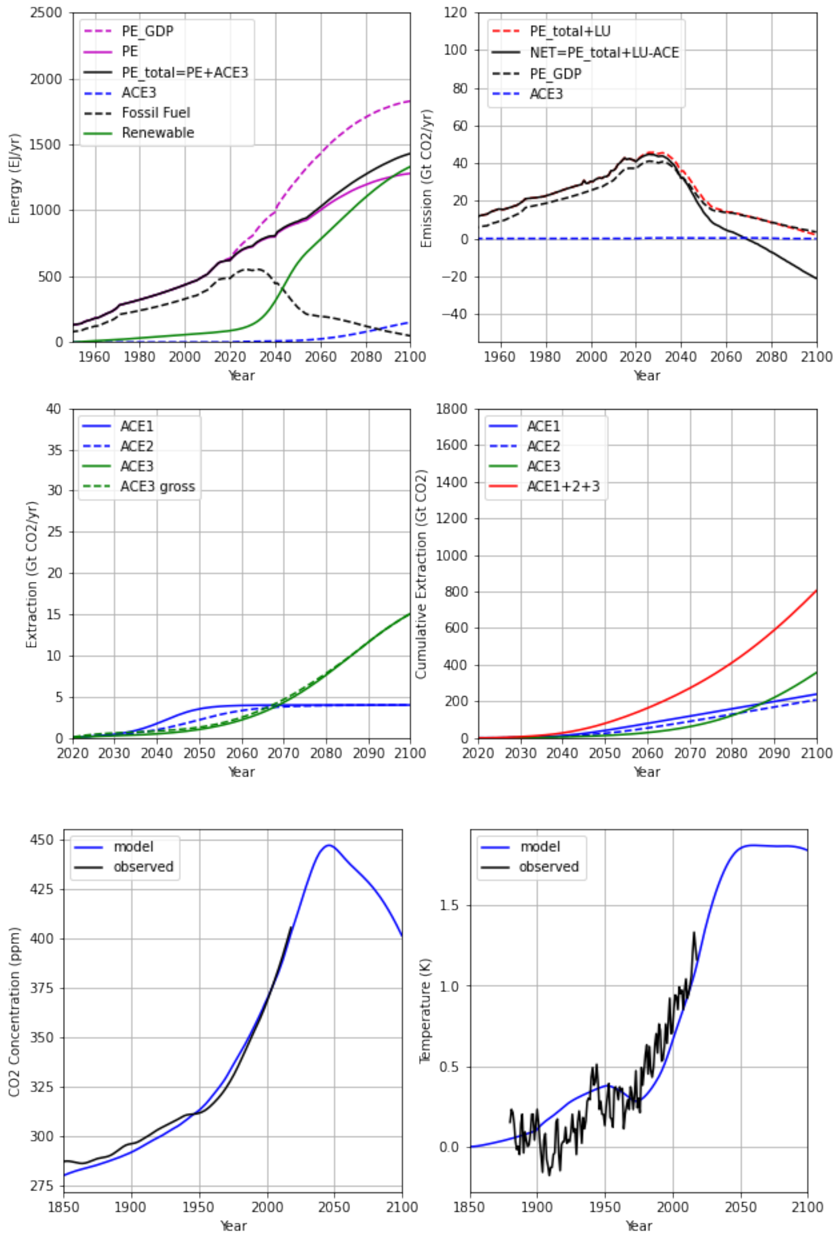

Fig. S2-12. Base version of the model, but including mitigation of non-fossil fuel SLCPs, in addition to fossil fuel sources. Also shown in Fig. 5.

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