ENERGY-CLIMATE SCENARIOS OF EXCURSION-AND-RETURN: A DEMONSTRATION EXERCISE

ATTACHMENT D.5-A – NARRATIVE - March 2021

This **ATTACHMENT D.5-A – NARRATIVE** describes the energy-climate model used in this exercise and reports key results.

ATTACHMENT D.5-B – MODEL shows the model itself and displays all figures and tables.

ATTACHMENT D.5-C – DATA shows source data used in construction of the model and the exercise.

ENERGY-CLIMATE SCENARIOS OF EXCURSION-AND-RETURN: A DEMONSTRATION EXERCISE

A. INTRODUCTION

It's been known for some time that if global mean surface warming is to be kept from exceeding 2.0˚C relative to pre-industrial levels we will need to reduce net global carbon emissions by 50-90% by mid-21st century and by 100% well before century's end.[1] [2] It's been acknowledged that this will be very difficult to do.[3] [4] [5] [6] [7]

The present exercise proceeds on the assumption that the 2.0˚C ceiling is in fact no longer a realistic possibility. It assumes that we can no longer credibly suppose that the world community will be able to agree upon and successfully implement the necessary national and international policies and programs, mobilize the enormous public and private sector financial commitments needed, produce and deploy the necessary technological innovations, decommission the global fossil-fuel industrial complex and replace it with a renewable energy complex of comparable scope and scale, and realize the universal transformation of social, cultural, economic and political values, beliefs, institutions and life-ways necessary to support a transition of such magnitude, all within the 30-50 years or so that the 2.0˚C ceiling requires.

This assumption is not a happy one. If correct, it means that the human community will have to learn to live with levels of warming that we had hoped to avoid while at the same time working all the more assertively to prevent warming from rising to 2.5˚C, 3.0˚C or higher.

Specifically, this exercise suggests that we might need to live with global mean surface warming that rises above 2.0˚C beginning about 2075, peaks at ~ 2.4˚C by about 2120, and returns to below 2.0˚C by about 2190. We characterize trajectories of this sort as *excursion-and-return*.[8]

The 115 or so years we spend above 2.0˚C will be years of unprecedented ecological, economic and societal loss and damage. But to let this grim prospect be cause for despair and resignation only ensures a future many orders of magnitude grimmer. At present there is no reason to expect that the level and duration of warming just noted would trigger or give rise to catastrophic harm that would be experienced as "the end-of-the-world".[9] [10] [11] [12] [13] [14] Human life and the planet that sustains all life will continue, albeit battered and bruised. Our goal must be to ensure that our children, grandchildren and great-grandchildren sustain and conduct themselves during the worst periods of this crisis in such a manner that their own children, grandchildren and great-grandchildren will have internalized what is necessary to ensure that similar or analogous global crises never again need come to pass.[15] [16]

B. THE MODEL AND THE EXERCISE

We constructed a simple energy-climate model that extends through the year 2400. Much of the model's climate sector draws on elements of the **FUND Model** developed by Tol and Anthoff (2019). The full energy-climate model and all figures and tables cited in this narrative are displayed in **ATTACHMENT D.5-B – MODEL.**

We prepared a Baseline scenario showing the growth trajectories of key demographic, economic and energy resource values, along with the implications of this growth for key environmental values, over the period 2010-2400. For initial Baseline values we drew on the **IIASA Shared Sustainable Pathways (SSP) database** [Version 2.0, Dec. 2018]. Specifically, we took elements of the IIASA **Scenario SSP-2-60** as our Baseline scenario for the period 2010-2100. See **APPENDIX 1** for more on the structure of the model and our use of the SSP scenario database.[17] [18]

It's no surprise that the Baseline scenario generates clearly unacceptable outcomes. In this exercise we modify this scenario in step-wise fashion to successively generate more acceptable outcomes, taking care to assess the practicability of each step. Our objective is to arrive at a scenario the outcomes of which might be judged to be both acceptable and practicable.

In this exercise the outcome variables of interest are global mean surface temperature and sea level rise. We don't attempt to further calculate losses and damages.

Our policy variables are 1) the mix and trajectory of primary energy resources used over time and 2) the use of carbon capture and sequestration (CCS) technologies. The model's energy portfolio includes four non-renewable primary energy resources – coal, oil, gas, and nuclear – and four renewable energy resources – solar, wind, hydro and biomass. See brief specifications of each of these in **APPENDIX 2**. Speculative sources of primary energy are reviewed in **APPENDIX 3**. The model considers CCS technologies of two sorts: those that capture emissions before they enter the earth's atmosphere and those that extract CO_2 from the ambient air. See further description and discussion of these in **Section D** below and in **APPENDIX 4.** In **APPENDIX 5** we consider the possible use of solar radiation management (SRM). We model and discuss uncertainty in **APPENDIX 6** and alternative population trajectories in **APPENDIX 7.**

The availability of non-renewable energy resources is generally not a constraint for energy-climate scenarios that terminate by 2100, but over longer periods such stock constraints are germane. Our model tracks the rate at which ultimately recoverable stocks of non-renewable energy resources are depleted. For renewable energy resources the model tracks constraints imposed by the availability of suitable land area and the rates at which capacity can realistically be installed at scale. [19] [20]

All of our scenarios incorporate the same Baseline trajectories of world population, GDP and primary energy use. See **Figures 1-7** and **Table 1**.[21]

This demonstration exercise uses a very simple model to assess very complex energy, climate and policy dynamics over a very long period. **Section E** assesses the results and considers ways in which the model and the exercise might be modified to present a stronger and fuller analysis. **Section F** offers closing comments. **TABLE A** shows selected key results.

C. DESCRIPTIONS OF THE CORE SCENARIOS

We prepared four core scenarios of primary energy use as shown in **Figures 8-11**:

Scenario A – Baseline
Scenario B – Balanced Renewables
Scenario C – Mostly Solar
Scenario D – Accelerated Mostly Solar

In all four scenarios annual primary energy use more than doubles between 2010 and 2100. Upon reaching 1,185 EJ/y in 2100 our scenarios show annual primary energy use remaining constant at that level through 2400. This abrupt transition from a growth trajectory to a no-growth trajectory is of course unlikely, but the abruptness itself doesn't make a significant difference in the long-run model outcomes. More significant is the assumption that at some point near the turn of the century global primary energy use will cease to grow, effectively forever.[22] [23]

Table 2a shows the stocks of ultimately recoverable non-renewable energy resources – coal, oil, gas and nuclear – available as of 2000. **Figures 12-15** show the stocks of these available at any point in time given the trajectories of use shown in Figures 8-11.[24] **Table 2b** shows the estimated maximum practicable flow of energy that might be supplied by solar, wind, hydro and biomass. See Appendices 2.b and 2.c for brief notes on non-renewable stocks and renewable flows respectively. **Table 3** shows shares of total primary energy supplied by each energy source for each of our four scenarios as of 2400. See **ATTACHMENT D.5-C – DATA** for source data on both non-renewable stocks and renewable flows.

The output trajectories of emissions, atmospheric CO_2 concentration, radiative forcing, mean surface warming and sea level rise generated under each of our four core scenarios are displayed in **Figures 16–20** and **Table 4.**

Figures 21-23 and **Table 5** show the land areas required to support biomass, solar and wind energy under each of our four scenarios.

The four core scenarios rely solely on **mitigation** – the use of prices, technologies, policies and changes in behavior to reduce CO_2 emissions. We explore other means of addressing global warming – in particular those involving carbon capture and sequestration - after we see how far mitigation alone might get us. [25] [26]

SCENARIO A – BASELINE

Our Baseline scenario for 2010-2100 is based on IIASA Scenario SSP-2-60. Among the IIASA inventory of scenarios SSP-2-60 is a very moderate *policy* scenario. IIASA's own baseline scenarios assume no significant new policies on climate change over the coming century other than those in place immediately prior to the 2015 UNFCCC Conference of Parties in Paris. With respect to the SSP-2 baseline scenario, the SSP-2-60 policy scenario shows a reduction of 9.2% in total primary energy use, a 19% reduction in fossil fuel use, and a resulting reduction in projected 2100 warming from 3.8˚C to 3.1˚C. This happens to be close to the level of warming that might be expected under the 2015 Paris Agreement if all signatories fully meet their nationally determined contributions (NDCs) but make no further commitments (or make them but don't realize them).

Our Baseline Scenario A then goes beyond the IIASA scenario terminal year of 2100. In Scenario A total primary energy use ceases to grow as of 2100 and the share that each of the eight primary energy fuels contributes to total energy use in 2100 continues unchanged through 2400. [27] [28]

Some might interpret this to be an historic socio-political achievement, as we've brought an end to both the growth of fossil fuel use and the growth of energy use in general. Unfortunately, the level at which the growth of fossil fuel use has ended is much too high. Figures 19-20 show that by 2400 global mean temperature has risen to 8.4˚C, that sea level has risen by 6.4 meters (21 feet) and that both values continue to rise thereafter.

Scenario A is not only undesirable but is unrealizable in the first place. Figure 12 shows that under Scenario A all oil stocks are exhausted by 2170 and all natural gas stocks by 2180. The immense stock of coal could be drawn upon to replace these two now depleted fossil fuels but would then itself be exhausted within about 200 years. Nuclear resources might then be called upon as a last resort but would be exhausted within less than a century.

SCENARIO B – BALANCED RENEWABLES

Scenario B displays an energy use trajectory for 2010-2100 identical to that of Scenario A. After 2100, however, the world begins a steady transition to 100% renewable energy: solar, wind, hydro and biomass. The 250-year span over which this transition completes itself is roughly the span over which the world initially transitioned from a mostly renewable biomass energy regime to the mostly non-renewable fossil fuel regime we've had since mid-20th century.

We see that Scenario B is no more acceptable than is Scenario A. The continued build-up of atmospheric CO_2 over the 250 years of the transition generates warming of 7.2˚C by 2400. Sea level will have risen to 5.8 meters (19 feet) by 2400 and continues to rise thereafter.

Scenario B is also problematic given the large share of primary energy supplied by biomass. Biomass energy is theoretically potentially carbon-neutral and some believe could even serve as a carbon sink. But it requires enormous land acreage and fresh water and thus competes directly with food, forage, natural fibers, timber, biodiversity, human habitation and more. The 362 EJ/y generated by biomass in Scenario B as of 2340 would require some 34 M km^2 of land. This is an area equivalent to ~ 70% of all agricultural land, or ~ 40% of all agricultural and forested land together, currently available world-wide. [29]

SCENARIO C – MOSTLY SOLAR

The warming and sea level outcomes under Scenario B make it clear that we'll need to move much more rapidly to minimal or zero net carbon emissions than Scenario B provides. **Scenario C – Mostly Solar** does this in several ways. First, the transition to an absolute decline of CO_2 emissions begins in about 2080 rather than 2100. [30] Further, once the decline begins it proceeds more rapidly than it did in Scenario B. The transition to a world of 100% non-fossil fuel energy is completed by 2280, seventy years earlier than is the case in Scenario B.

A portion of the Scenario C transition is achieved by a significant increase in the use of nuclear power as a bridge technology in the early and mid-22nd century. By 2260 nuclear is phased out and fully replaced by solar.

Solar, wind and biomass energy each present challenges that need to be overcome if they are to supply major shares of total primary energy. Biomass as noted faces the challenge of land and water use, while solar and wind face the challenge of variability.[31] For Scenario C we make the provisional judgement that the challenges presented by solar and wind energy can more readily be overcome than can those presented by biomass energy. Thus in Scenario C solar and wind energy ultimately supply over 86% of the world's primary energy while biomass provides less than 9%.

Unfortunately these several initiatives towards a world of zero fossil fuel use are too little too late. Global mean temperature rises to 5.0˚C by 2340 and effectively stabilizes near that level. Sea level rises to 4.7 meters (15.4 feet) by 2400 and will continue to rise at least until all land ice is gone.

SCENARIO D – ACCELERATED MOSTLY SOLAR

Scenario D displays a trajectory of emissions mitigation that for purposes of this exercise we posit is likely to be as ambitious as is credible. It shows a significant and sustained absolute decline in global CO_2 emissions beginning by 2050 – just 30 years from this writing. And it further accelerates the overall pace of transition. The world is fossil-fuel free by 2170 rather than by 2250 as in Scenario C. These more ambitious targets are not unrealizable, but they will likely require the sort of sustained mass mobilization, and the major transformation of social, cultural and political values, currently advocated by few outside the most committed sectors of the environmental activist community.[32]

Scenario D relies once more, and to a somewhat greater degree, on the use of nuclear power as part of a bridging strategy. Nuclear energy use peaks at 183 EJ/y in 2120 but is phased out in favor of solar by 2250. Under Scenario D biomass energy is completely phased out in favor of solar by 2130.

Figures 22-23 show that the 100% non-fossil fuel energy regime of Scenario D would require about 4.0 M km^2 of land area, an area just about 50% of that of the continental United States. The most intense period of infrastructure build-out would be the five decades 2050-2100, during which our new solar and wind energy infrastructure would need to expand nearly seven-fold, from 0.47 M km^2 to 3.14 M km^2. This calls for a global build-out of ~ 53 K km^2/y, an area roughly the size of the combined areas of the U.S. states of Massachusetts and Vermont. It entails a rate of expansion of about 11% annually during the first decades and about 2% annually over the final decades. Although the scale is unprecedented these rates appear to be consistent with experience and reasonable projection.[33] Note, however, that this renewable energy build-out needs to proceed in tandem with a) the conversion and adaptation of our residential, industrial, commercial, transport and other end-use systems, and b) the decommissioning, repurposing, dismantling, recycling and disposing of the infrastructure of our legacy global fossil fuel industrial complex. All together this transition will be the largest, most intense and most extensive coordinated human effort of any sort in all of human history. [34] [35]

Under Scenario D warming rises above 2.0˚C in 2075, peaks at 2.8˚C in 2150, declines to below 2.0˚C by 2300, and continues to decline very slowly after that. We live for nearly a quarter of a millennium over 2.0˚C. Sea level rises from 0.7 m (2.3 ft) in 2100 to 2.4 m (7.9 ft) in 2400, and appears unlikely to peak within less than several centuries thereafter.

As noted, Scenarios A, B, C and D are scenarios of pure mitigation, that is, they rely on the use of technology, prices, alternative fuels, changes in consumption and lifestyle practices and other means to reduce the amount of CO_2 and other GHGs initially produced. We've pushed our conventional mitigation options to the presumed maximum level practicable and it's not enough. What is to be done?

At present the most commonly suggested recourse is **carbon capture and sequestration**, as discussed in the next section.

D. SCENARIOS INVOLVING CARBON CAPTURE AND SEQUESTRATION

Carbon capture and sequestration (CCS) captures post-combustion CO_2 just before or at any time after it enters the atmosphere. The captured CO_2 is sequestered in deep sedimentary rock strata or is stored in biomass. As conventional CO_2 emissions mitigation appears increasingly less likely to allow us to avoid a 2.0˚C warming, CCS has been receiving focused attention.

Two major categories of CCS are considered further in this demonstration exercise. *Point-source* or *emissions CCS* captures CO_2 at its point of origin at fossil fuel power plants, industrial sites and mines and wells. *Stock CCS* extracts previously emitted CO_2 directly from the ambient air.

Point-source CCS uses *mechanical* collection and compression. Stock CCS uses *mechanical*, *biological* and *chemical* means. The major method of mechanical stock CCS known as *direct air* CCS (DACCS) uses large fans to push or pull air across grids coated with chemicals that adsorb CO_2. Biological stock CCS includes afforestation and reforestation, improved agricultural, coastal and forest management, and the use of the combustion residue *biochar* as a soil amendment. Enhanced weathering of silicate rock surfaces coated with reactive applications might also capture large quantities of CO_2. See **APPENDIX 4b** and **ATTACHMENT D.5-C – DATA, Tab C** for more on all of these.

A form of CCS that uses both mechanical and biological elements is Biomass Energy with Carbon Capture and Storage (BECCS). With BECCS, biomass is burned to generate electricity and the CO_2 combustion product is immediately captured and conveyed via pipeline to its sequestration site. BECCS thus offers the double benefit of directly substituting for fossil fuel use and of ensuring that its own CO_2 emissions never enter the atmosphere. However, the results of full life-cycle assessments of BECCS suggest that its net contribution to negative emissions might be small or even positive. This, along with concerns about its land and water requirements, have diminished the role foreseen for BECCS. [36]

In this demonstration exercise we focus on the potential use of point-source CCS and direct air CCS (DACCS).[37] [38] In both technologies the captured CO_2 is compressed and injected into porous layers of deeply buried sedimentary rock capped by impervious rock strata. This would be done using deep wells already available following completion of fossil fuel extraction or through newly drilled injection shafts. [39] [40] [41]

Point-source CCS and DACCS facilities in operation today are mostly very small and still in the developmental stage. Neither technology is ready for the planetary-scale deployment called for in many of the scenarios informing the near-term national and international policy debate. [42] [43] [44] [45]

Figures 24-25 show quantities of CO_2 that might be captured by emissions and stock capture technologies applied at moderate and ambitious scales over several centuries. These trajectories are described further in DNs 46-48.[46] [47] [48]

Both point-source CCS and direct air CCS, like BECCS and other CCS technologies, require careful evaluation across their full life-cycle to determine how much of a net contribution they can actually be expected to make to reducing atmospheric carbon concentration and thus surface warming. DACCS, in particular, is energy intensive, and it needs to run on fully renewable energy sources if it is to be of net benefit. **Figures 26-27** show the global energy requirements and consequent land requirements (in this exercise, for PV solar) of our ambitious DACCS scenario shown in Figure 25. These energy and land requirements are large but appear to fall within practicable bounds. [49]

Figures 28-32 and **33-37** show how emissions and stock CCS might be applied, at both moderate and ambitious levels, to *Scenario C - Mostly Solar* and *Scenario D - Accelerated Mostly Solar*. Selected outcomes of these applications are displayed in **Table 6** and **TABLE A** (p10). [50] [51]

Regarding **Scenario C – Mostly Solar** we see that the ambitious application of both emissions capture and stock capture technologies gives us a warming trajectory that rises above 2.0˚C in 2070, peaks at 4.0˚C in 2210, declines very slowly to 3.2˚C by 2400 and appears unlikely to fall below 2.0˚C for at least another two centuries or so. Sea level has risen by about 3.7 m (12.1 ft) by 2400 and appears likely to remain near that level for quite some time. Few if any would consider these conditions acceptable.

In the case of **Scenario D – Accelerated Mostly Solar** we see that the ambitious application of both emissions and stock capture technologies gives us a warming trajectory that rises above 2.0˚C in 2075, peaks at 2.4˚C in 2120 and then declines until it returns to below 2.0˚C in 2190. We will have spent 115 years above 2.0˚C. By 2240 warming has declined to below 1.5˚C, and if we choose to continue with CO_2 stock capture warming will decline further. Sea level rise peaks at about 1.6 m (5.2 ft) in 2310 and declines slowly after that. [52]

E. ASSESSMENT

Is Scenario D + ambitious CCS an acceptable outcome? Many people consider even 2.0˚C to be unacceptable and argue for a ceiling of 1.5˚C or lower. The 2.4˚C ceiling of Scenario D + ambitious CCS is 20% warmer than 2.0˚C, and climate scientists generally believe that loss and damage rises exponentially with warming. While there is at present no compelling evidence that one or more globally catastrophic warming-related events would be triggered in the run-up to 2.4˚C, the risk of such an event certainly increases as warming rises.[53] A 1.6 m sea level rise would inundate huge areas of inhabited coastal land worldwide. Many other harms are anticipated.

On the other hand, our 2.4˚C warming is a peak, not a new long-term equilibrium. While loss, damage and risk would be increasing for 45 years (2075-2120), they'd presumably be decreasing for the remaining 70 years (2120-2190) and would continue to do so thereafter. Sea level, of course, would continue to rise. But it would do so very slowly, perhaps no more than 4-5 cm (1.6-2.0 in) per decade between 2050 and its peak in 2310. At that slow rate much loss and damage might be avoidable. Sill, much loss and damage – from warming as well as sea level rise - will *not* be avoidable, and in those situations the moral claim on the part of impacted communities for redress by the world's wealthy would be strong.

Is this final scenario – "Accelerated Mostly Solar + Ambitious CCS" - practicable? The levels and rates of change of the important mitigation and CCS values appear to be consistent with historical experience and reasonable expectation given the magnitude of the crisis. The fact that we achieve net zero global carbon emissions by 2120 rather than the currently advocated 2050-2075 allows additional time (~ 2-3 generations) for the necessary, historically unprecedented technological, economic, socio-cultural and political transformations of human life and civilization to be worked through with some degree of collective intention rather than imposed by other means.

This final scenario at least suggests practicability. Acceptability can only be determined through political engagement.

It's important to reiterate that this is a demonstration exercise in which many important elements have been left out or greatly simplified. In the construction of the model many assumptions were made that might produce results that make our situation appear significantly more or less dire than it is in fact. Stronger and fuller analysis is needed if exercises similar to this one are to be even minimally useful. Elements of such an analysis are briefly noted in the next section. [54]

Elements of a Stronger and a Fuller Analysis

1. The single most determining assumption of this exercise is that Scenario D – "Accelerated Mostly Solar" – is the most ambitious mitigation scenario realistically possible. If this is not so – if the Scenario D emissions trajectory shown in Figure 16 can be made to decline significantly sooner and more rapidly - then the rest of the exercise as presented counts for little. A stronger and fuller analysis would justify this, or another, emissions mitigation scenario as the most ambitious possible rather than simply positing it to be so as we've done here. [55]

2. The model doesn't include **economic components** that might allow the many costs and benefits generated in the course of the several scenarios and policy applications to be reflected in the outcomes. We neither compute nor assume a social cost of carbon. Nor does the model include either regional sectors or sectors modeling population stratification by income and wealth. [56]

3. In this demonstration exercise we make no attempt to model **probabilities and uncertainties.** A stronger and fuller analysis would do so. See **APPENDIX 6** for an example of a test of the model's sensitivity to uncertainty in the climate sensitivity parameter.

4. In the present exercise population, per capita GDP, aggregate levels of primary energy use and their rates of growth are all exogenous to the model and independent of one another, and all their rates of growth or decline collapse to zero as of 2100 and remain there indefinitely. How might alternative understandings regarding these rates of change and their interdependence, with each other and with other variables in the model, make it easier or more difficult to construct practicable and acceptable energy-climate policy scenarios? See **APPENDIX 7** for an illustration of the impact that alternative **population** trajectories might have on warming and policy.[57]

5. Global scenario exercises are often obscure about the ways in which they measure and incorporate the dynamics of ***technological innovation.*** In this exercise we implicitly adopt the IIASA SSP-2-60 trajectories of energy intensity, carbon intensity and total factor productivity for 2010-2100, and then posit that these values stabilize at their 2100 values for the following 300 years. On first reading this scenario element might appear to be unrealistic. But if we include even small increments of steady intensity or productivity improvements over two or three centuries we end up with similarly unrealistic results.[58] In both instances the innovation/efficiency/productivity assumptions overwhelm all other factors and drive the trajectories of the system. More attention to this dynamic is needed if long-run energy-climate exercises such as ours are to be useful.

6. Our choice of SSP-2-60 as our Baseline scenario through 2100 is a conservative choice. That scenario assumes only moderate, incremental change in the overall structure, tenor and direction of global industrial civilization over the coming 80 years. The solutions we call on to address climate change – rapid reduction of fossil fuel use, massive build-out of both a global solar-wind energy regime and a carbon capture and sequestration industrial complex, along with nuclear as a temporary bridging power source – are compatible with, and probably only with, such a globalized industrial world. It could be instructive to explore several of the SSP scenarios that consider as their Baseline a world of significantly ***less economic growth, less population and less industrialization***. [59] [60]

7. Energy sources that are unlikely to contribute significantly, if at all, to total primary energy supply before 2100 could be assessed regarding contributions they might be in a position to make after that time. These energy sources include ***nuclear fusion, nuclear breeder reactors, photovoltaic hydrogen*** and ***regional-scale geothermal energy***. For each potential energy source we'd need to sketch an R&D timeline, justify a date at which grid-level contributions might begin, suggest rates at which the infrastructure of the new source might be built-out and to

what final levels, and consider any challenges the new source poses or faces that might slow or preclude its eventual widespread use. See **APPENDIX 3** for brief preliminary notes on these sources.

8. If one or more forms of CCS are developed to a point of low cost, high efficacy, high safety and high public acceptability we might reconsider our decision to have vast stocks of fossil fuels left in the ground. Limiting factors would include the availability of secure sequestration sites and the magnitude of harms other than climate change posed by the use of fossil fuels.[61] [62] [63] If we learn to live fulfilling lives with a constant level of primary energy supplied by renewable energy resources there would be little reason to entertain either the reintroduction of fossil fuels or the development of the "hard" energy resources just noted above.

9. We could see if there might be a role that any of the geoengineering technologies noted in **APPENDIX 5** might play. These technologies come with severe risks and most would likely be justifiable only under extraordinary circumstances, i.e., for limited periods to avert truly catastrophic outcomes for which no other remedies are available within the relevant time-frame. See **APPENDIX 5.c** for an exploratory example using the form of solar radiation management know as ***stratospheric aerosol injection (SAI).*** In the example we use SAI to reduce peak warming from the 2.4˚C we achieved in our final scenario, that of maximal mitigation plus ambitious CCS, to preferred peak levels of 2.2˚C and 2.0˚C.

F. CLOSING COMMENTS

If it's no longer reasonable to expect that we can keep global warming from exceeding 2.0˚C we need to address questions of the sort sketched in this exercise. What are the benefits, costs and risks of alternative excursion-and-return climate policy trajectories? What level of peak warming is acceptable? Is it preferable to peak and decline as rapidly as possible, as gradually as possible, or to proceed in some other manner? What energy and related technologies, social and economic policies, and political and cultural commitments are likely to serve us well during the difficult years that we spend above 2.0˚C? [64]

As noted, this demonstration exercise uses a very simple energy-climate model, makes many simplifying assumptions and leaves important questions unaddressed. Researchers with access to more fully developed energy-climate models could usefully explore scenarios of excursion-and-return above 2.0˚C.

Along with technology, policy, conventional political organizing and full-on grassroots movement building, we'll need different ways in which to think and talk about the trajectories of our individual and collective lives, and about those of our children, grandchildren, great-grandchildren and further on, under conditions of excursion-and-return. Our understanding of our situation and the language we use to express it will likely need to be different from that which we've had and used, with uncertain results, to date. [65] [66]

#   #   #

TABLE A. GLOBAL MEAN SURFACE WARMING UNDER ALTERNATIVE SCENARIOS

		A	B	C	D	E	F	G	H
	SCENARIOS	first year > 2.0°C	peak warming	year(s) of peak warming	year returning to ≤ 2.0°C	year SAI begins	year SAI ends	total years > 2.0°C	total years of SAI
	MITIGATION ONLY								
1	Scenario C - MOSTLY SOLAR	2070	> 5.0°C	> 2400	~ never	na	na	~ forever	0
2	Scenario D - ACCELERATED MOSTLY SOLAR	2075	2.8°C	2150 (2130-2170)	2300	na	na	225	0
	MITIGATION + AMBITIOUS CCS								
3	Scenario C - MOSTLY SOLAR + CCS	2070	4.0°C	2210 (2180-2240)	~ 2650?	na	na	~ 600?	0
4	Scenario D - ACCELERATED MOSTLY SOLAR + CCS	2075	2.4°C	2120 (2100-2140)	2190	na	na	115	0
	MITIGATION + AMBITIOUS CCS + SAI								
	Scenario D - ACCELERATED MOSTLY SOLAR + CCS + SAI								
5	+ Moderate SAI (2.2°C peak)	2080	2.2°C	2110 (2100-2130)	2170	2050	2170	90	120
6	+ Maximum SAI (2.0°C peak)	never	2.0°C	2100 (2080-2110)	always ≤ 2.0°C	2050	2200	0	150

Columns

A	The year in which warming first exceeds 2.0°C. Scenario 6 never exceeds 2.0°C.
B	The level of peak warming for each Scenario. Warming in Scenario 1 reaches 5.0°C in 2400 and continues to rise thereafter.
C	The year in which warming peaks, plus the range of years during which warming is within 1/10 degree of the peak. Scenario 1 rises continually and shows no peak before 2400.
D	The year in which warming returns to 2.0°C or below. In Scenario 3 warming declines very slowly and may even stabilize above 2.0°C.
E	For Scenarios 5 and 6, the year in which SAI begins.
F	For Scenarios 5 and 6, the year in which SAI is discontinued.
G	For Scenarios that peak above 2.0°C and then return to ≤ 2.0°C, the number of years above 2.0°C. Scenarios 1 & 3 might never return to ≤ 2.0°C. Scenario 6 never exceeds 2.0°C.
H	For Scenarios 5 and 6, the number of years in which SAI is in operation.

Notes

1. The numbering system 1-6 for the scenarios applies to this Table, to Table AB (p 37) and to Table G.2-2 (p 39), but is not used elsewhere in this exercise.
2. In scenarios 3-6 "ambitious CCS" means the use of ambitious emissions CCS and ambitious DACCS, together, as shown in B-Model Tab A, Figure 25.

ACKNOWLEDGMENT

I'd like to thank Dr. Juan Pablo Carvallo of Lawrence Berkeley National Laboratory for his invaluable assistance, on-going consultation and careful critique at every point in the preparation of this demonstration exercise. The views and opinions expressed here don't necessarily state or reflect those of Lawrence Berkeley National Laboratory or of Dr. Carvallo. – RH

DISCUSSION NOTES

[1] For estimates of the amounts by which global carbon emissions must be reduced over the course of this century to avoid undesired climate change see Walsh et al. (2017), van Vuuren et al. (2016), Loftus (2015), IPCC (2014), IIASA (2012), Rogelj et al. (2011) and Matthews and Caldeira (2008).

[2] To avoid repetition of the technically correct term "global mean surface temperature above pre-industrial levels" we use "warming," "surface warming," "surface temperature," "global warming" and similar terms, as well as the initials "MSW," as synonyms unless otherwise noted or clear from context.

[3] The authors of fifteen papers prepared between 2011 and 2016 stated their belief then that it is highly unlikely that we will be able to avoid a 2.0˚C warming; see *Attachment D, pp D.1-2* of this working paper. Authors writing more recently have even more firmly declared a 2.0˚C ceiling to be an unachievable target; see Osaka (2020), Frost (2019) and Lawrence et al. (2018). The most recent IPCC Assessment Report, AR5 (2014), presented 116 scenarios in which warming is stabilized at or below 2.0˚C; all but 15 of these require the near-immediate (~ 2015-2020), massive and rapid global deployment of carbon capture and sequestration (CCS) technologies. See Fuss (2014).

[4] Analysts have noted that many of the scenarios used to inform policy on climate change systematically tend to understate the challenges we face. Many argue that assumptions concerning the **rapid adoption and eventual scale and efficacy of CCS** are unrealistic. See Fajardy (2019), Muri (2018) and Smith (2015); see also DN 44 below. Other analysts believe that the rates at which **carbon intensity** ($GtCO_2$/$GDP) is shown to decrease in the IPCC AR5 scenarios are an unrealistic departure from historic experience and reasonable projection. See Jenkins and Cole (2015). Loftus et al. (2015) show that even the most conservative of a set of 17 noted scenario exercises display **energy intensity** (EJ/$GDP) declining at 1.5–1.8%/y over the coming half century while the historical decline over 1970-2010 has been 0.8%/y. Energy intensities used in this demonstration exercise are shown in Figure 5 and Figure 6 of *ATTACHMENT D.5-B – MODEL Tab A. graphics display*. Values for 2010-2100 are the IIASA SSP-2-60 scenario data base values. These values show higher than historical rates of energy intensity decline for the first half of the 21st century (a 2010-2050 average decline of 1.6%/y) but the rate of decline declines steadily over that period and for 2050-2100 roughly fluctuates around a value of 1.0%/y. For our extension to 2400 we show the rate of energy intensity decline declining from 1.1%/y in 2100 to 0.0%/y in 2150. Energy intensity itself reaches a value of 1.76 EJ/10^12 $GDP and stays at that level through 2400. Admittedly, it's difficult to imagine such diffuse and over-determined technological phenomena as the decline in energy intensity coming to an absolute end. But it's also difficult to imagine energy intensity itself effectively approaching zero, which is what happens if it continues to decline at 1.0%/y for another few centuries. This conundrum is an aspect of the more general conundrum involving economic growth and technological innovation that we encounter throughout this working paper; see *II. Key Challenges, pp 12-14*; also *DNs 84-91.* We don't address the evolution of carbon or energy intensity further in this demonstration exercise, but a fuller inquiry would need to do so.

[5] IPCC reports may have underestimated the rate at which mean surface temperature has been increasing. The latest revision of the Hadley Centre Climatic Research Unit Temperature (HadCURTS), one of three authoritative data sets used by the IPCC, suggests that estimated mean surface temperature from pre-industrial times to 2018 has risen by 1.07˚C. This is an 18% increase over the previous estimate of 0.91˚C, and shortens the estimated time we have before baseline warming exceeds levels of 1.5˚C and 2.0˚C. See Morice et al. (2020) and Vaughan (2020).

---

[6] Note that the human community will need to agree not only on schedules of global and national carbon emissions (with direct bearing on prospects for economic growth) but on who bears what share of the costs that the coming energy-climate transition will entail. In what ways and by how much should wealthier countries compensate poor countries for damages they unfairly suffer? How much should countries pay simply because of their greater or lesser ability to do so, regardless of culpability or victimhood? In what ways and by how much should affluent households within any given country compensate their less well-off fellow-citizens for hardships unfairly endured? On these and related issues of climate equity see e.g. Baer et al. (2000) and Athanasiou (2020).

[7] While it's encouraging that as of November 2020 over 110 countries have pledged net zero carbon by 2050, recent reports give reason to view such pledges with caution. See notably UNEP's *Emissions Gap Report 2020* and *Production Gap Report 2020*. The former shows that countries are lagging far behind the minimal emissions reduction pledges they made in Paris for 2030. The latter documents the continued global expansion of fossil fuel infrastructure that locks in high levels of coal, oil and gas production and use for decades to come. For similar critique see Manley and Heller (2021), Watson et al. (2019), Sachs (2019), Burck et al. (2018) and Nachmany and Mangan (2018). While political leaders are putting their names on paper the global fossil fuel complex is putting facts in the sky.

[8] Studies exploring such excursion-and-return scenarios include those of MacMartin et al. (2018), Lowe et al. (2009), den Elzen and van Vuuven (2007), Wigley et al. (2007), and Huntingford and Lowe (2007). Most recently and of special interest is the extension by Meinshausen et al. (2020) of the canonical SSP scenarios to year 2500. Nine such scenarios were constructed, all of which show some measure of excursion-and-return. The study was published too late to help inform the present exercise but should figure in any extensions. It's rightly objected that adoption of an excursion-and-return strategy as policy could create a moral hazard: we cooperate during the early period in which less sacrifice is required and then defect during the subsequent more difficult period. This prospect is another argument for the importance of learning to make and abide by collective commitments over time horizons of 100-200 years and longer, as discussed in *Attachment E.7* of this working paper.

[9] For the case that it is very unlikely that a warming of 2.0˚C will trigger catastrophes of "end-of-the-world" magnitude see Walker (2019) and Piper (2019). See *Attachments D.1 and D.4* of this working paper for related discussion.

[10] Kriegler et al. (2009) surveyed 43 scientists concerning their subjective assessment of the probability that warming of various levels would trigger one or another of four consequential events: 1) a major restructuring of the Atlantic meridional overturning circulation (AMOC); 2) melting of the Greenland and West Antarctic ice sheets; 3) the die-back of the Amazon rainforest; and 4) the intensification of the El Niño-Southern Oscillation (ENSO). The authors interpreted the survey results to suggest a 16% probability that at least one of these events would be triggered by a warming of 2-4 °C above year 2000 levels, i.e., ~ 2.6-4.6°C above pre-industrial levels; and further, that warming above ~ 4.6°C posed a 56% chance of catastrophic triggering. This conclusion would suggest that a warming of 2.4°C, although certainly likely to generate severe loss and damage, might be outside of and below the level likely to trigger truly catastrophic loss and damage.

[11] Many studies have catalogued likely loss and damage that might be expected at varied levels of warming. *The Economics of Climate Change* by Nicholas Stern (2006) offers an array of such impacts associated with warmings of 2.0˚C and 3.0˚C. These might be thought of as lower and upper bounds for likely impacts associated with our 2.4˚C peak warming:

> **2.0˚C:** 20-30% decrease in water availability in vulnerable regions; sharp declines in crop yield in tropical regions; 40-60 million more exposures to malaria in Africa; 10 million more people threatened by annual coastal flooding; more than 15% of species facing extinction; high risk of polar bear extinction.
>
> **3.0˚C:** Serious decadal droughts in Southern Europe; 150-550 additional millions at risk of hunger; 1-3 million more deaths from malnutrition; 1-178 million more people threatened by annual coastal flooding; more than 20% of species facing extinction.

Note that these estimates show impacts that can be expected if no action is taken to prevent, adapt to or compensate for particular damages caused by the warming. Clearly, such action will be enormously costly and socially and politically disruptive. But it is still far more likely that action will be taken rather than not.

[12] The NGO CarbonBrief (2018) compiled results from 70 peer-reviewed climate studies to compare the differential impacts on environmental values expected under increasing levels of warming. Nearly 1000 comparisons are displayed, of which five are shown here by way of illustration:

Condition	***2.0˚C***	***3.0˚C***
1. Probability of an ice-free arctic summer in any one year	16%	63%
2. Total rainfall during West African rainy season, relative to 1971-2000	+10%	+7%
3. Area burned by wildfires in average Mediterranean summer, relative to 1971-2000	+62%	+97%
4. Additional days per year when ave max temp of British Isles is > 86°F, rel to 1971-2000	1 day	2 days
5. Increase in average annual rainfall in "all of Asia," relative to 1861-1900	+6%	+10%

While many of the ~ 1000 displayed perturbations would clearly be at least regionally disastrous, and in some instances regionally catastrophic, considered as a whole they do not appear to suggest "the-end-of-the-world."

[13] DNs 9-12 are not in any way meant to downplay the objective harms that a warming of 2.0-2.4˚C would almost certainly visit upon us. They are rather meant to support the contention that even under such circumstances we would have a world well worth fighting for. There are, of course, a great many studies that might be interpreted to argue differently, and a stronger and fuller exercise would address these studies. See DN 14 (following) for a note on one such recent report. See also the studies referenced in DN 54.

[14] ***Climate Reality Check*** by Spratt et al. (2020) argues that the "end of civilization" due to climate disruption is "… likely unless dramatic global action is taken…" The report is serious and well-referenced. It suggests that warming is on track to exceed 1.5˚C by 2030, 2.0˚C prior to 2050, 3.0˚C in the second half of this century and perhaps 5˚C by 2100. It argues that "… 2˚C would be extremely dangerous; 3˚C catastrophic; and 4˚C unlivable for most people." It says that once we cross 1.5-2.0˚C, *trigger cascades* could render any subsequent attempts at climate control futile. It calls for ***zero global emissions by 2030***, massive CCS deployment, and a willingness and readiness to use solar radiation management. To achieve these goals the governments of the world will need to make climate disruption their first political and economic priority. Again, I won't address these arguments further here but a stronger and fuller exercise would need to do so.

[15] The case that we still have a realistic chance to prevent warming from ever exceeding 2.0˚C rests on an assessment that as the impacts of warming begin to be felt more acutely, and as concerned citizens continue to organize with increasing passion, a mass socio-political transformation supporting both necessary policies and major changes in way-of-life will emerge, grow and prevail. Advocates cite as encouraging signs the rise to prominence of such new grassroots efforts as Sunrise Movement, *Skolstrejk för klimatet* and Extinction Rebellion; the growing number of global elite finance and investment concerns now taking the climate crisis seriously; the rapid declines in the production and use of coal and in the cost of renewable energy; and the growing number of countries, states, municipalities and major national and global institutions pledging carbon neutrality by mid-century. See Wallace-Wells (2021), McKibben (2020) and Leber (2019). Some advocates ground their hopes in theories of non-linear consciousness change and movement building. See Roberts (2020) and Otto et al. (2020).

[16] I should be clear that I hope that we are able to prevent warming from exceeding 2.0˚C and that I strongly support the many efforts to do so. Efforts of these sorts will be more necessary than ever, and in fact will need to be redoubled many time over, if at some point it becomes clear that the 2.0˚C ceiling is no longer an option.

[17] For a full description of the Shared Socioeconomic Pathway 2 scenarios see Fricko et al. (2017). For an early outline of the SSP scenario framework see O'Neil et al. (2014). For a later full account of the SSP framework see Riahi et al. (2017).

---

[18] We use the demographic and economic values of SSP-2-60 and its trajectory of primary energy supply through 2100. We use other sources for carbon intensity of each primary energy source; see *ATTACHMENT D.5-B – MODEL, Tab D.1 params energy* for sources and derivation. The SSP-2-60 scenario for 2010-2100 was generated using the MESSAGE-GLOBIOMS model developed by and maintained at IIASA, while we use the more basic miniFUND model. In the SSP-2-60 Baseline scenario mean surface warming as of 2100 is 3.2˚C, while our Baseline Scenario A shows warming of 3.1˚C.

[19] Renewable energy and CCS technologies face constraints and challenges not considered in this exercise. These include their own operating energy requirements (we do review this for DACCS, see DN 49), life-cycle management including waste disposal (e.g. of deteriorated wind turbine blades and PV panels), impact on terrestrial albedo (afforestation/reforestation in snowy upper latitudes can reduce surface albedo), impact on wildlife and other environmental values (birds and bats killed in wind turbines), negative impact on soil nutrients and water use, high capital costs and other market entry barriers, public opposition (wind turbines off Cape Cod), and obsolete transmission infrastructure and sketchy regulatory structures in and among countries. See Seetharaman et al. (2019), Gauthier (2018) and Firestone (2007).

[20] Although the price of renewables is falling dramatically, innovation is allowing fossil fuel prices to drop as well. Fossil fuels retain long-standing direct and implicit subsidies. Although more than 40 countries have imposed some form of tax on fossil fuels, the levies, which have generally run $10-$25 US/metric ton CO_2, are well below the $50-$150/ton that has been suggested as approximating the social cost of carbon. The Obama administration was criticized by environmentalists for its low-ball SCC value of $51/ton; the Trump administration predictably set the SCC at $1/ton. In December 2020 the New York State Department of Environmental Conservation (2020) announced that the official “Value of Carbon” was henceforth $125/ton (methane was pegged at $2,782/ton and nitrous oxide at $44,727/ton). The Biden administration initially resurrected the Obama administration value of $51/ton but subsequently appointed a working group that will likely recommend it be higher. In February 2021 noted economists Nicholas Stern and Joseph Stiglitz (2021) called on the Biden administration to adopt a SCC at “…the upper end of the $50–100 range.” The SCC is a function of a host of normative factors and subjective judgments and so its value is ultimately and properly a political decision.

[21] All figures and tables referenced in this *ATTACHMENT D.5-A – Narrative* are shown in *ATTACHMENT D.5-B – MODEL*, unless otherwise noted.

[22] It might be objected that any scenario in which primary energy use more than doubles over the course of this century is, from the perspective of ecological sustainability, moving in quite the wrong direction. From the perspective of resource equity, however, the situation is more complex. Our scenarios show global primary energy use per capita at the beginning of this century at 73 GJ/c and rising to 125 GJ/c by 2100. In 2013 per capita primary energy use in the United States was 290 GJ/c, while such countries as Bolivia, Nigeria, Guatemala and Paraguay each made do with about 33 GJ/c. If by 2100 all countries are to have access to equitable, i.e., roughly equal, shares of global primary energy, the United States will need to *reduce* its per capita primary energy use to less than half the amount it enjoyed in 2013, and the four developing countries just noted would have a right to the use of almost four times as much primary energy as they use today. Levels of global primary energy use in 2100 lower than the 1185 EJ/y used in this exercise would make it far more challenging to construct a pathway towards energy equity. As a rule the introduction of equity and justice values into global energy-climate discussions – which is necessary and unavoidable – requires environmentalists to significantly expand the ambit of their ethical concern. For more on the equity dimensions of climate change and policy see the important resources at EcoEquity and Climate Equity Reference Project.

[23] In the mid-1990s noted energy scholar John Holdren (who later served two terms as science advisor to President Barack Obama) proposed that by 2100 we could have a sustainable, just and fulfilling world running on a stabilized 945 EJ/y of renewable energy resources. He wasn’t proposing some global hippie utopia, but he did envision a more locally-sourced, less materially acquisitive and less frenzied world. In 2005 Nobel Laureate (in chemistry) Richard Smalley suggested that providing all people with a life roughly equivalent to that of a modest middle-

---

income family in today's developed world would require 1890 EJ/y, precisely twice the level that Holdren had proposed. In 1995 global Total Primary Energy Supply [TPES] was about 408 EJ/y. Thus Holdren, a committed environmentalist, was calling for a world of 2100 that consumed 2.3 times as much primary energy/y as we were consuming in 1995, and the mainstream Smalley was calling for a world consuming 4.6 times as much. In 2018 IIASA presented their 26 SSP scenarios with global primary energy use in 2100 ranging from a low of 490 EJ/y to a high of 1825 EJ/y. In all 26 scenarios primary energy use is *lower* than the 1890 EJ/y proposed by Smalley. Further, energy use in 14 of IIASA's scenarios is lower than that advocated by Holdren. My point is that the 2100 TPES of 1185 EJ/y used in the present exercise may already embody what many would consider strongly ecological and counter-consumerist values. See Holdren (1995), Smalley (2005) and IIASA (2018).

[24] The three major nuclear power technologies – fission, breeder fission and fusion – differ dramatically in their supply potential, developmental prospects, safety issues and more. The value of 80,000 EJ we show for ultimately recoverable nuclear fuel stocks is a placeholder value pending more careful review. It might be considered a high estimate for uranium used in conventional light-water reactors or a low estimate for uranium and thorium used in breeder reactors. In any event the ultimate stocks of nuclear fuel don't figure importantly in this demonstration exercise, as we rely on nuclear only as part of a short-term bridging strategy. See *ATTACHMENT D.5-C – DATA, Tab A.9 Nuclear Fuels* for notes on the potentials for nuclear power.

[25] The real world of course doesn't work this way. The human community won't try mitigation-only until 2400 and then if it finds the results unsatisfactory go back to 2100 and try something else. The scenario sequence we use here helps display the discrete contributions of different approaches to addressing climate change, and in particular that of different means and levels of carbon capture and sequestration (CCS). Scenarios using CCS are introduced after we assess the potential of mitigation-only scenarios.

[26] In this demonstration exercise we focus on the role and mitigation of CO_2 emissions. We show the warming impact of other greenhouse gases, notably methane (CH_4), nitrous oxide (N_2O) and sulfurhexaflourides (SF_6), as a single exogenous constant of 0.3 W/m^2 of additional radiative forcing. See **Appendix I.c**. Atmosphere and Climate Sector, Equation (8), for more.

[27] For examples of climate and climate policy studies that extend their models beyond 2100 see MacMartin et al. (2018), Meinshausen (2011), Solomon (2009) and Wigley et al. (2007). Among other topics, these studies investigate the rate at which CO_2 concentration and global mean temperature would decline following the abrupt termination of CO_2 emissions. All found this rate of decline to be very slow. Land and sea plant biota convert atmospheric CO_2 into new biomass. Some portion of this remains as permanently larger biomass stock but most returns to the atmosphere within decades via decay, combustion and fermentation. Final removal and deposit of carbon in buried land strata and deep ocean sediments happens over millions of years. In addition, as the oceans absorb heat from the warmed atmosphere they progressively become less able to absorb further heat; see Frölicher et al. (2013). The energy-climate model used in the present exercise is calibrated to reflect this long persistence of atmospheric CO_2 and consequent warming; compare Figures 16-19.

[28] The flat trajectory of primary energy use after 2100 points to an eventual world of flat output growth as well, albeit not necessarily immediately. Output can continue to grow while primary energy use does not so long as technological innovation, or more generally total factor productivity (TFP), continues to grow. But what exactly *is* TFP, what are its determinants, how is it measured and how is it sustained? In conventional economic growth theory the output attributable to TFP growth is measured as the residual after the contributions of capital, labor, natural resources and entrepreneurial ability have been taken into account. But this formulation just dodges the questions. In truth nobody really knows what TFP or technological innovation actually *are*, or, more charitably, there are no generally accepted formulations. The most insightful qualitative account I know of is that offered by the physicist and economist R. U. Ayers (1992); it's discussed at length in *Section II.C* of this working paper.

[29] Wind, solar and biomass energy systems all require large parcels of land, but acre-for-acre biomass is by far the most land-intensive. In our model the ratio of wind to solar to biomass land area needed to produce the same EJ/y is very roughly 1-10-180. As noted, biomass also requires enormous quantities of fresh water, further putting it in

---

competition with humans, animals, farming and industry; see also DN 36. Further, biomass plantations engineered to maximize growth of particular feedstocks can negatively impact soil nutrients. A suggested partial alternative to the use of agricultural or forest land to grow dedicated energy crops is the collection and combustion of dispersed feedstocks - forest products wastes, agricultural residues, organic fractions of municipal solid wastes, paper, cardboard, food waste, green waste and other organic waste – but this approach is inefficient and energy intensive. It hasn't gone unremarked that among the most enthusiastic advocates of the widespread adoption of biomass energy is the fossil fuel industry. On the positive side, biomass can be converted directly into ethanol, biodiesel and other liquid fuels, whereas solar and wind cannot. And the massive expansion of solar and wind as shown in our Scenarios C and D requires innovations in energy storage that have thus far remained elusive, whereas biomass is an energy store in itself. For more on the prospects for biomass energy see Reid et al. (2019), DeCicco et al. (2018) and Harper (2018).

[30] I use the phrase "transition to an absolute decline" to mark that period over which the growth of aggregate global CO_2 emissions ceases to be positive and then proceeds to become largely continuously negative. Figure 16 shows that in Scenario C the transition to an absolute decline occurs over the period 2080-2090; in Scenario D it occurs over the period 2050-2060. In neither instance does this mean that mitigation efforts over the three-to-five prior decades have been for naught. Rather, the late date of these transitions is meant to take into account the many often antagonistic elements that will need to be reconciled if we are to stop and then reverse the growth of global CO_2 emissions. Political coalitions in a critical mass of the world's countries will need to agree on mitigation policies and put them into effect; solar, wind and other new energy infrastructure will need to be built-out at an accelerated pace for many decades worldwide; new industries of the size and reach of today's fossil fuel industry (e.g. the coming "carbon industry") will need to be founded, financed, and expanded. Opposition, skepticism and inertia among both elites and the general populace will need to be overcome. Even when good faith consensus has been reached on policies and programs, routine "frictional" forces can add months or years to the period before measurable benefits begin to be realized. Meanwhile, continued necessary and desirable economic growth in the developing world, even legitimately "green" growth, will tend to offset CO_2 emission reduction initiatives of the developed world for at least several decades to come.

[31] Power systems are designed to meet demand at any and every moment in time, a feature known as *resource adequacy.* Any electrical grid that includes large amounts of solar and wind capacity needs to account for the short-term variability and annual seasonality of these renewable energy resources. Resource adequacy can be enhanced with clean resources such as hydropower (using reservoirs and pumped hydro), but is constrained by geography. Expanded transmission capabilities and interconnection of grids can greatly enhance resource adequacy. See Kroposki (2018). Demand response – controllable customer loads through direct or indirect mechanisms – are technically capable of providing short-term ancillary services for high renewable penetration grids. See Ma et al. (2013). Battery, flywheel, and other types of chemical and physical storage are widely regarded as necessary components of high renewable penetration systems. The costs of batteries has dramatically declined over the last two decades, and is expected to continue to decline. See Kittner et al. (2013) and Cole and Frazier (2019). Nascent technologies such as underground thermal storage and hydrogen electrolysis during periods of excess solar power production active areas of R&D.

[32] The suggestion that 2170 is the soonest we can realistically expect to achieve a world of zero CO_2 emissions through mitigation alone is a strong claim and needs justification. Figure 16 suggests that the trajectory of CO_2 emissions under Scenario D has three phases. From 2020-2040 global CO_2 emissions continue to rise, but this aggregate record masks important achievements of finer grain. During this period the developed world comes to an effective popular consensus that compels political change that will finally allow an absolute decrease in CO_2 emissions in the developed world to begin. The developing world continues to emit increasing quantities of CO_2 but at steadily declining rates, as an initially necessary fossil fuel-intensive industrial infrastructure is replaced by lighter infrastructure and new technology. Further, over this period the remaining technological barriers to an energy future free of fossil fuels are resolved. All of this creates the conditions necessary so that as of 2050 the second phase begins: an absolute, continuing real decline in global CO_2 emissions. Over the subsequent 80 years, from 2050 to 2130, CO_2 emissions drop by 93%, from 45.6 to 3.4 $GtCO_2/y$. We have achieved the effective elimination of global CO_2 emissions over the course of a single long human lifetime. During the third and final

---

phase, running the 40 years from 2130-2170, we root out the last remaining 3-4 $GtCO_2$ of emissions from particularly difficult-to-substitute-for sources, e.g. the use of carbon-based substances as industrial feedstocks for chemicals, plastics, steel and cement, and for large jet aircraft and ocean freight shipping.

[33] A rule of thumb for large, long-term energy infrastructure construction is "an order of magnitude per decade," or 23%/y; see McQueen et al. (2020). Kramer and Haigh (2009) surveyed the growth of major twentieth-century energy-related infrastructures and found that during their initial decades of diffusion these grew exponentially at average annual rates near 26%, but after having established a secure market presence transitioned to considerably lower linear growth rates. Iyer et al. (2013) reviewed the growth histories of thirty-eight energy technologies and found that while national diffusion could proceed rapidly, with typical annual growth rates of 12-18%, global expansion took place at the much lower annual rates of 2-6%. Realmonte et al. (2019) cites estimates that solar PV has been expanding at annual rates of 30% in recent years and that wind energy is expected to grow at rates of 11% through 2050.

[34] The potential for bottlenecks and critical shortages, e.g. of essential scarce metals and specialized engineering talent, is obvious and calls for proactive policies. See GreenPeace SEA (2020), Mishra (2018), Blagoeva (2016) and Hu & Cheng (2013).

[35] Along with the half-century global build-out of new primary energy infrastructure and new end-use systems, and the dismantling of the global fossil fuel infrastructure, we'll likely need to add the build-out of a global carbon capture and sequestration infrastructure, as discussed in Section D below.

[36] The ability of BECCS to serve as a net negative carbon sink depends upon features of the cropland geography and soil, plant species removed and newly planted, and management practices employed. Muri (2018) shows, for example, that if tropical forest lands are cleared and then used as BECCS plantations, net carbon emissions over the life cycle are *positive*. Muri also finds that if mid-latitude temperate forests are converted to BECCS plantations, net carbon emissions could be negative but their magnitude would be small. Like biomass energy in general, BECCS is also problematic regarding land and water use. Fajardy et al. (2019) use data from Fajardy and MacDowell (2017) to show that an international BECCS industry established to remove 12Gt CO_2/y would use 3.6-9.7 billion m^3 of fresh water annually, and then note that in 2019 water used for agriculture world-wide totaled ~ 8 billion m^3. BECCS also raises concerns regarding the complexity of its deployment at the planetary scales required; of the social acceptability of extensive and intrusive biomass production; of transport and conversion; and of the difficulty of providing sufficient feedstock. For further assessment of BECCS see Minx et al. (2019), Gough et al. (2018) and Fuss et al. (2018).

[37] The several photosynthetic CO2 uptake and capture technologies have different applicabilities and cost and capture profiles, and all of these vary greatly across the many world locales in which they would operate. Point-source and direct air CCS are intended to be modularized and routinely operable regardless of locale. Still, we can think of the moderate and ambitious CCS policy trajectories shown in Figures 23-24 as envelopes that might be filled with mixes of the ten CDR technologies displayed in **Appendix 4b.** Our 12 $GtCO_2$/y ambitious stock capture trajectory, for example, might remove 8 $GtCO_2$ via DACCS and 2 Gt each using afforestation and biochar. Alternatively, DACCS might remove 6 Gt, reforestation and enhanced weathering 2 Gt each, and land management 1 Gt; and so on. A stronger and fuller exercise could explore such options, paying attention of course to their varying energy, water, land and other resource requirements, and other merits and complications as well.

[38] Large-scale afforestation and reforestation can be considered a form of CCS, especially when planned explicitly for that purpose. In that case the siting, choice of tree or other growth species, management plans and more would be decided with CCS as the guiding objective. However, most of the carbon locked up in trees and other vegetation eventually returns to the atmosphere via combustion, decay or fermentation. Forestation can be helpful as part of a short-term (100-150 year) carbon capture strategy to buy time while new energy and carbon removal technologies come on line, but its long-run value depends on the development of treatments that arrest decay and secure permanent mass storage. See **Appendix 4b.A** for more on this.

---

[39] Point-source CCS has an advantage over direct air CCS in that CO_2 is highly concentrated in the combustion exhaust streams (flue gas) that it draws upon. However, with point-source CCS the captured and concentrated CO_2 most often needs to be transported via pipeline some distance to its sequestration site. DACCS has an advantage over point-source CCS in that its facilities could in most cases be constructed on or very near its sequestration site. But DACCS is disadvantaged in having to pull or push massive quantities of air through its chemical collector apparatus in order to capture the desired quantities of CO_2. Tree-like passive DACCS structures that don't rely on volumes of forced air have been constructed but are barely beyond proof-of-concept. See Siegel (2019).

[40] Terminology regarding what we're calling carbon capture and sequestration (CCS) is unsettled. Other general descriptors include *carbon removal technologies* (CRTs), *carbon dioxide removal* (CDR), *negative emissions technologies* (NETs) and the colloquial *carbon scrubbing*. Proposals in which the captured CO_2 is used as part of an industrial process (e.g. for jet fuel, enhanced oil recovery or carbonated beverages) rather than being sequestered are referred to as *carbon capture and utilization* (CCU). The terms *sequestration* and *storage* are mostly interchangeable, although "sequestration" can be used to imply permanency and "storage" can imply possible removal for utilization at some future date. Some authors use "CCS" alone to mean what we're calling *point-source* CCS and others call *post-combustion* CCS. Many authors treat such point-source capture as a mitigation technology rather than a capture technology. The term *industrial carbon removal* (ICR) has been used to include both point source and direct air carbon capture and to distinguish these from capture via biological or weathering processes. Some authors differentiate *mechanical DACCS* (using heavy metal fans, etc.) from *biological DACCS* (using plants that grow).

[41] Point-source CCS and both mechanical and biological DACCS have been criticized for their potential role in helping extend the life of a global fossil-fuel industrial complex that should be shut down for good as soon and completely as possible. Full life-cycle analysis makes it clear that these carbon capture technologies capture little if any net carbon unless powered by non-fossil fuels. Neither can they be net carbon sinks if captured CO2 is utilized, e.g. for enhanced oil recovery, rather than buried forever. Environmentalists are wary of government R&D funding for private sector CCS that might more effectively be spent on R&D for solar, wind and other renewables. As noted, the prodigious quantities of energy and thus land required by mechanical DACCS raises strong concerns of both impact and feasibility. Environmentalists have been divided regarding CSS, with many younger, grassroots groups opposing it as part of a more general distrust of industrial mentality, culture and scale, while many older and centrist environmental groups see its strategic potential if the energy source and CO2 destination concerns are fully met. See Levy (2020), Sekura and Lichtenberger (2020), Cohen (2019) and Climate Advisors (2018).

[42] As of 2019 only a handful of moderately large facilities world-wide employed CCS. The fossil-fuel power plants at Boundary Dam in Canada and Petra Nova in Texas, and the Illinois Industrial facility owned by Archer Daniels Midland, each capture about 1 Mt/y of the CO_2 they emit. See Folger (2019). Four small BECCS facilities also operate in the U.S. and Canada, and three larger facilities are planned for Japan, United Kingdom and Norway. See Consoli (2019). Only two initiatives are underway to develop large commercially viable DACCS systems. The Swiss firm **Climeworks** is building truck-sized modular units that can each capture about 40 metric tons CO_2/y and be stacked in assemblies of several dozen or more almost anywhere in the world. **Carbon Engineering**, a Canadian firm led by Harvard climate scientist David Keith, has built a single large demonstration plant that extracts ambient CO_2 and transforms it into liquid fuels and other commercial products. Carbon Engineering is building a larger plant that will extract 1 Mt CO_2/y. See Gertner (2020). The 12 Gt/y of stock capture called for in our ambitious stock capture scenario (Figure 25), would entail construction and operation of 12,000 such large DACCS facilities, or, alternatively, about 300,000,000 of the modular Climeworks units, perhaps assembled into e.g. 1 million operational facilities of 300 modules each.

[43] Most current CCS developers are working to find commercial markets for the carbon they sequester, as part of overall plans to support and expand their ventures. Climeworks is looking to supply CO_2 to the carbonated beverage industry, and Carbon Engineering, as noted, is developing liquid fuels. It is widely acknowledged, however, that commercial markets for CO_2 at the scale needed to avert unwanted climate change are unlikely to develop. Rather, the viability of CCS will depend upon the willingness of governments to establish a fair price for carbon and to pay CCS enterprises for the carbon they sequester. Many CCS entrepreneurs are working with a

---

goal of being able to capture and sequester CO_2 at a cost of $100/ton. At this price the moderate and ambitious CCS regimes used in this exercise imply industries with annual revenues of $900 billion and $2.1 trillion, respectively. This compares with estimated 2019 global commercial oil and gas production revenues of $3.3 trillion. Alternatively, CCS could be operated by the public sector, as is, for example, national defense. For a sense of scale note that the 2019 U.S. Defense Department budget was $732 billion, and that total defense spending by all the world's countries in that year was $1.92 trillion.

[44] Many analysts have expressed concern, even alarm, at the many energy-climate scenarios that incorporate what they believe are highly unrealistic assumptions concerning the rate at which CCS technologies can be developed and brought into use. These two statements are representative:

> "… [A] substantial gap exists between the upscaling and rapid diffusion of NETs implied in scenarios and progress in actual innovation and deployment. If NETs are required at the scale currently discussed, the resulting urgency of implementation is currently reflected in neither science nor policy." Minx et al. (2018).
>
> "[S]uch expectations may be seriously over-optimistic… [P]utting a hypothetical [NETs] technology into a computer model of future scenarios is rather different than researching, developing, constructing and operating such a technology at the planetary scale required to compensate for inadequate mitigation." EASAC (2018).

On the same note see also Fajardy et al. (2019), Muri (2018) and Smith et al. (2015).

[45] Recent reports have outlined the sorts of R&D programs needed as the very first and immediate step towards a global-scale CCS capability. A U.S. National Academy of Sciences Consensus Study Report (2019) proposed a $400-1,000 M research program to be mostly completed over the subsequent 10-20 years. Smith et al. (2015) said that the cost of scaling up BECCS for biofuels and electricity as part of a global 2.0˚C ceiling strategy would be $66 B/y as of 2030 and $261 B/y as of 2050. As a necessary immediate step they proposed construction of 5-10 large BECCS demonstration facilities at a cost of $1B each. They said that it would be reasonable to assume that NETS of some sort will someday have some useful role to play in climate management, but that given the many uncertainties and narrow time-window it would be a grave mistake to rely on NETS as part of a 2.0˚C ceiling strategy. See also Folger (2019), which details past and current U.S. federal funding for CCS-related research activities. Funding for 2003-2018 averaged $330 M/y; in FY 2018 this support totaled $727 M.

[46] Estimates in the literature regarding the maximum quantity of CO_2 that might be removed by emissions and stock capture, and of the capture quantities necessary to avoid warming above particular ceilings, understandably vary greatly, both because of uncertainties regarding these untested technologies and because they would be employed as parts of ensembles including other untested technologies operating within untested policy frameworks. Estimates from this literature are compiled in *ATTACHMENT D.5-C – DATA, Tab C. Carbon Capture.* Our moderate and ambitious programs of emissions and stock capture use conservative estimates meant to take into account the many contingencies that their development, deployment and operation at global scale in a fractious world would entail.

[47] The moderate and ambitious *emissions* capture scenarios, reaching a maximum of 3 and 9 $GtCO_2$, respectively, can apply to Scenario C through 2400. They apply to Scenario D for only a much shorter period, because the more ambitious Scenario D mitigation trajectory drives CO_2 emissions to zero by 2170. Thus in conjunction with Scenario D emissions capture CCS is a *one-time, time limited* operation. Moderate emissions CCS is needed for only 110 years (2060-2170) and ambitious emissions CCS for 140 years (2030-2170).

[48] We show maximum *direct air* CCS to be 12 $GtCO_2$/y, although estimates as high as 30-40 $GtCO_2$/y have been entertained. We show maximum DACCS capacity over the five decades 2050-2100 growing at annual linear rates of about 152 $MtCO_2$/y, whereas some studies, e.g. Realmonte et al. (2019), imply that rates as rapid as 1.5 $GtCO_2$/y

---

might be feasible. Note that 12 $GtCO_2$ is no small quantity; it's about 50% of total global CO_2 emissions in 2000. See *ATTACHMENT D.5-C – DATA, Tab C. Carbon Capture* for the full set of estimates.

[49] DACCS consumes enormous quantities of energy as it forces ambient air across the chemically adsorbent grids that capture CO_2. Energy is also used in the process of cleaning and recharging the grids, and concentrating and sequestering the CO_2. During its period of maximum capture our ambitious DACCS operation consumes 150 EJ/y, about 13% of our total world primary energy supply of 1185 EJ/y, and would require an additional 714,000 km^2 of land for PV solar, a land area slightly smaller than that of Chile. See *ATTACHMENT D.5-B – MODEL, Tab D.1 params – energy***.** It's reasonable to imagine that rather than reduce global primary energy being used for other purposes by 13% in order to power DACCS, the human community would raise the energy ceiling to (1185 + 150) 1335 EJ/y, as shown in Figure 26. These are large numbers but they don't appear to be deal-breakers. Our 1185 EJ/y global ceiling was chosen to allow a comfortable life on a populous planet without overtaxing our energy systems or endangering the environment, and there is room for another 150 EJ/y, at least for a limited period. The supply is available as well. In *ATTACHMENT D.5-C – DATA, Tab B. Flows - Renewables* we estimate that solar PV could supply up to 3000 EJ/y indefinitely.

[50] Importantly, DACCS applied to Scenario D, like point-source CCS, is a *one-time, time-limited* technology. Figure 36 shows that under Scenario D + ambitious CCS mean surface temperature drops below 2.0˚C in 2190, 1.5˚C in 2240, and 1.0˚C in 2290. Those dates are marked in Figure 25 by the small black dots on the light brown DACCS trace. The human community has the option of quite literally pulling the plug on DACCS at any of these marker dates (or any other date). Once the plug is pulled MSW would continue to fall, albeit more slowly than if DACCS was still in service. We would have to decide between the costs of keeping DACCS in operation and the benefits of returning more quickly to a safe and comfortable MSW. If the latter is somewhere between 2.0˚C and 1.0˚C, DACCS would have a total systems lifetime of 150-250 years.

[51] We don't show CCS applied to Scenarios A and B because such applications would be for naught. CCS might be able to pull the outcomes of Scenario D into arguably acceptable territory, but it is not able to do so for Scenario C. Scenarios A and B are thus lost causes.

[52] In theory there is presumably some point at which the concentration of atmospheric CO_2 is no longer high enough to make further stock capture of net benefit. Economists would identify this as the point at which the marginal benefit realized by extracting an additional unit of CO_2 from the atmosphere (i.e., marginal damages avoided) is less than the marginal cost of doing so. It's questionable how meaningful this sort of marginal analysis is over these geographic scales, inter-generational time spans and levels of aggregation and abstraction. See Pindyck (2015) and Gambhir et al. (2019) for skeptical assessments. Benefit/cost analyses might best be included in a basket of quantitative and qualitative assessments informing an ultimately and properly political decision.

[53] See again DNs 9-14.

[54] Any of several developments, were they to come to appear likely or even possible, would make it more difficult to defend a climate strategy of excursion-and-return involving a peak above 2.0˚C. One would be the discovery of some planetary mechanism that is triggered when warming surpasses some value above but close to 2.0˚C and could cause catastrophic harm. See Steffen et al. (2018), which sketches the possibility of *tipping cascades* in which a mechanism triggered at a particular level of warming generates further warming sufficient to trigger some other warming mechanism, and so on. See also Lenton et al. (2019) and Cai et al. (2016) for reviews of additional potentially catastrophic tipping-points. Another, and happier, development would be that one or more of the speculative energy technologies noted in **Appendix 3** are made to work successfully, safely and economically, and are able to be deployed world-wide far more rapidly than currently appears to be feasible. A third is that we find our understanding of climate science to be in error and that warming builds much more slowly than we now anticipate, giving us time to respond more effectively at less cost. A fourth would be the emergence of a global religious or analogous movement in which much of the human community quickly comes to adopt values, beliefs and behaviors that result in a rapid reduction of carbon dioxide emissions. At present there is no indication that

---

any of these developments are likely, but in the nature of such cases that's to be expected.

[55] Our assumption that Scenario D is the most ambitious mitigation scenario possible rests upon a series of component assumptions concerning trajectories of, among other factors, population energy intensity (J/capita) and carbon intensity (gC/J). Our assumptions concerning these are conservative to a fault - we assume that they improve minimally through 2100 and after that remain constant. This is consistent with our desire to avoid the common dodge of saying that technology will save us; but a stronger and fuller analysis would at least review the literature and consider reasonable efficiency improvement scenarios. That literature is immense. For now we briefly note two recent studies that make the case that technological improvements in energy and carbon intensity could deliver carbon mitigation scenarios far more ambitious than that shown in our Scenario D:

1) In ***Carbon-Neutral Pathways for the United States*** Williams et al. (2021) construct a business-as-usual reference scenario and eight deep decarbonization scenarios that show alternative paths by which the United States can achieve carbon neutrality by 2050. Key elements of all scenarios include 1) strong energy efficiency improvements; b) ambitious electrification; c) decarbonized electricity; and d) biomass carbon capture. In the least cost "Central Case" scenario per capita energy use in 2050 has dropped to 70% of that in the reference case. Wind and solar provide 57% of total primary energy; oil and gas provide 13% (mostly to cover renewable variability), biomass provides 12% and nukes provide 4%. By 2050 nearly 100% of light duty vehicles are EVs. The Central Case relies on existing commercial or near-commercial technologies. Total cost of the transition is 0.38% of 2050 U.S. GDP. The study helpfully specifies those actions that need to take place by 2030 if the 2050 objectives are to be met: "expand renewable capacity 3.5 fold, retire coal, maintain existing gas generating capacity, and increase EV and heat pump sales to >50% of market share." Williams notes that the major constraint on net zero 2050 is less the final practicability of the energy system than it is the pace at which it needs to happen.

2) In ***Rewiring America*** and its companion report *Mobilizing for a Zero-Carbon America* Griffith et al. (2020, 2020) argue that the U.S. can cut carbon emissions by 70-80% by 2035 and to zero by 2050, a path commensurate with 1.5˚C peak warming. The priority task is to achieve near-100% electrification of all end uses by 2050. The greater efficiency of electrification will allow a 50% reduction of total primary energy demand. The electricity will come mostly from solar and wind, supplemented by hydro, minor biofuels and perhaps limited nuclear. Every home must be retrofitted with rooftop solar, heat pumps, batteries and EVs. This will cost ~ $40,000/household, and government-backed low-interest "climate loans" would make this affordable. This decarbonization imperative will require a mobilization of wartime scale and intensity and will rely on mandates and direct command rather than on prices, markets or carbon taxes. A key challenge is the fossil fuel industry's many billions in stranded assets. The government should pay firms 10% of the value of these assets, to be used to retrofit for the new non-fossil fuel era. The total transition to renewables will create 30-40 million new jobs over the period 2020-2040 and will absorb all displaced fossil fuel industry and related employees.

These ambitious proposals invite skepticism. Strategically, however, it's not unreasonable to push a maximum program in the expectation that if net zero is not achieved by 2050 it will still be achieved sooner than if the maximum program had not been forcefully argued for in the first place. The obvious caution is that if the maximum is outlandishly ambitious credibility might suffer.

[56] See Peters and Geden (2017) for comment of the multiple real-world complications that a regional analysis brings to light. Nordhaus' RICE model (2010) shows 12 regions, Tol and Anthoff's MiniFUND model (2019) can be run with 16 regions, and the IIASA-SSP Database can be configured to display up to 32 regions.

[57] An increasing number of demographers question the common assumption that the rate of population growth will stabilize at or near 0% by the end of this century. They argue that with growing income, education, urbanization, communication, health care and access to contraceptives, fertility rates in most of the world will decline and likely stabilize below the replacement rate of 2.1 children/woman. Although most women may still have two children, the number who have one or no children will be greater than the number who have three or four children. Smaller populations are generally thought to imply less aggregate demand and thus reduced pressure concerning our nexus of energy/climate/economic concerns. But deep and sustained population decline

---

may have serious negative consequences regarding economic well-being and social stability. See Stein et al. (2020), Bricker and Ibbitson (2019), Coleman and Rowthron (2015) and Lutz et al. (2013). See also **Appendix 7** and ATTACHMENT *D.5-B – MODEL Tabs G.1-G.2* for a preliminary illustration of the impact that sustained population decline might have on CO_2 emissions, warming and other outcomes modeled in this exercise.

[58] Our model uses the middle-of-the-road IIASA SSP-2-60 values that show world per capita GDP growing from $25,200 in 2050 to $56,700 by 2100, at what today might be considered the rather modest annual rate of 1.7%. If per capita GDP continues to grow at that rate through 2400 it will grow to $6,900,000. What does this value even mean? As noted elsewhere in the working paper, it's as difficult for us imagine a world in which GDP grows forever as it is for us to imagine a world in which the growth of GDP has forever come to an end.

[59] The IIASA SSP database allows display of 26 unique scenarios. Our baseline scenario SSP-2-60 is close to the middle of these with respect to Population and GDP and somewhat towards the high end regarding Primary Energy Use and Global Mean Temperature:

Number of the 26 IIASA Scenarios with 2100 values that are:

	< SSP-2-60	= SSP-2-60	> SSP-2-60
Population	11	5	9
GDP	13		12
Primary Energy Use	20		5
Global Mean Temperature	20		5

This display suggests that there may be many opportunities to explore alternatives whose baseline assumptions are "greener" than those of SSP-2-60. It also reinforces the sense that the SSP scenarios as a whole may over-represent overly optimistic baseline assumptions. Nearly half the scenarios display higher GDP but lower primary energy use or lower warming in 2100 than does SSP-2-60, and fully one-third show both higher population and higher GDP than does SSP-2-60, yet still also show lower primary energy use and lowe*r* warming. On the other hand, this "optimistic" skew may simply be a function of the intent of the SSP construction exercise in the first place, i.e., to help enable us to explore a wide range of net beneficial future outcomes.

[60] Comparison of what might be considered the two most "green" SSPs elicits some observations:

SSP-1-26 shows total primary energy supply (TPES) very nearly stabilizing at ~ 560 EJ/y by 2030. This level is 47% of the moderate 1185 EJ/y we show for 2100 and after in this demonstration exercise. By 2100 TPES is supplied largely by biomass (40%), fossil fuels (30%) and solar (20%). Fifty-eight percent of biomass and 36% of fossil fuels are decarbonized via CCS. Warming peaks at 1.84˚C in 2075 and declines slowly to 1.76˚C in 2100. SSP-1-26 shows population peaking at 8.5 B in 2050 and then declining at increasing rates to 6.9 B by 2100. Depending on post-2100 trajectory assumptions (e.g. linear, exponential or logistic), world population according to SSP-1-26 would decline to between 0-1,000 people (yes, that's *zero* to *one thousand*) within ~ 150-300 years. Perhaps incongruously given collapsing population and flat TPES, SSP-1-26 shows World GDP increasing steadily and dramatically, from $102 trillion in 2020 to $565 trillion in 2100, an average annual growth rate of 5.7%.

SSP-2-19 shows TPES at 802 EJ/y in 2100, about 68% of the 1185 EJ/y level used in this demonstration exercise, but increasing rapidly; after 2040 TPES increases nearly linearly at a rate of 4.8 EJ/y each year. At this rate it would reach 1185 EJ/y in another 80 years. Energy in 2100 is supplied almost entirely by biomass (28%), wind (26%), solar (22%) and nuclear (10% but declining rapidly). Fossil fuels trail with 7%. Seventy-six percent of biomass energy is produced and decarbonized using BECCS. Forty-five percent of fossil fuel use is decarbonized by CCS in mid-century (2040-2060) when fossil fuel use is still substantial, but with fossil fuel use at minimal levels CCS is being phased out. Warming peaks at 1.64˚C in 2050, declines to 1.34˚C by 2100 and continues to decline after that. SSP-2-19 shows population peaking at 9.46 B in 2070 and then declining slowly to 9.03 B by 2100. In line with

---

roughly stable population and strong growth in TPES, SSP-2-19 shows World GDP increasing steadily and dramatically, from $101 trillion in 2020 to $505 trillion in 2100, an average annual growth rate of 5.0%.

[NB: Further analysis of the IIASA SSP scenarios is deferred pending the expected release of updated SSPs along with the IPCC AR6 in Summer 2021.]

[61] van Vuuven et al. (2013) cite studies by Hendriks et al. (2004) and IEAGHG (2011) that suggest global sequestration capacities of 500-10,000 $GtCO_2$ and 5,000-20,000 $GtCO_2$, respectively. These values suggest a mean estimate of ~ 3,000-15,000 $GtCO_2$. In our demonstration exercise our most ambitious CO_2 sequestration scenario requires capacity for 388 $GtCO_2$ over a span of ~350 years, which is well below the lower bound of this estimate. These estimates don't account for economic and socio-political factors, which typically constrain availability, but the magnitudes suggest considerable leeway.

[62] The possibility that we might someday find a way to use fossil fuels safely and economically raises new questions. For example: over the coming decades in which we transition to renewable energy resources, do we fully dismantle/recycle/dispose of the existing fossil fuel infrastructure or do we mothball some portion of it?

[63] Even if CO_2 emissions could be fully captured and sequestered there are reasons we might not wish to resurrect fossil fuels as a primary energy source. These include a) harmful land and habitat degradation at the sites of extraction and along the entire infrastructural chain of transport, processing, distribution, use and waste disposal; b) water and air pollution, much of it toxic, as waste water used in extraction and gaseous pollutants discharged in transport and combustion enter the water table and the atmosphere; and c) oceanic acidification as CO_2 and other fossil fuel combustion products enter the ocean.

[64] The consideration of excursion-and-return scenarios raises many additional less frequently encountered questions. How symmetric is the response of the climate system to a particular atmospheric temperature reached as part of a cooling trajectory rather than a warming trajectory? If some feature of, say, atmospheric circulation clicks into a new stable pattern after warming rises above some level, can we expect it to click back to its original pattern after reaching that same temperature on the way down? If ice sheets start melting as the atmosphere warms, do they start reforming as the atmosphere cools, like videos run in reverse? Once having adapted, at least partially and however fitfully, to warming above 2.0˚C, is it obvious that we should work to get back to and below 2.0˚C as rapidly as possible? Should our seawalls be built to last for millennia, or should they be modularized so as to be easily removed in segments as sea levels begin to fall? Energy-climate scenarios that include episodes of excursion-and-return will need to address such questions.

[65] Among other things, this new understanding will likely have what we now call "environmentalism" deeply integrated into the fullness of our lives and society, and in part as a consequence perhaps disappear as a separately understood way of thinking.

[66] The value of mythic narrative as an account of the human condition and prospect has been noted by thinkers from antiquity through the present. It's possible to imagine such narratives that could powerfully help the human community navigate the coming 100-200 years of the climate crisis. One common and applicable mythic narrative is that of the **Epic Journey and Return,** used in e.g. *The Odyssey* (Homer, 8th c BCE) and *The Ramayana* (Valmiki, 7th c BCE*).* Another applicable narrative is that of **Paradise, Sin, Expulsion and Redemption**, as told in e.g. *The Book of Genesis* (~ 6th c BCE).

# # #

APPENDICES

APPENDIX 1. THE LONG-TERM ENERGY-CLIMATE MODEL: STRUCTURE AND PARAMETER VALUES

1.a. KEY ELEMENTS

The model exogenously specifies global population, per capita GDP, sources and levels of primary energy supply and the rates of growth and decline of all of these, from 2010 through 2400. Alternative scenarios are developed by varying the trajectories of supply for each primary energy source, policies of carbon capture and sequestration (CCS) and stratospheric aerosol injection (SAI). Focal output variables are global mean surface warming and sea level rise. The model tracks the depletion of non-renewable energy resources, the land area required by renewable energy resources, and rates of renewable energy capacity build-out.

Values for the Baseline Scenario A for the period 2010-2100 are taken from a middle-of-the-road scenario prepared by IIASA in support of the work of the IPCC, in particular in the lead-up to the 2015 UNFCCC Conference of Parties in Paris. A full description of that scenario, designated **SSP-2-60,** can be accessed via the IIASA Shared Sustainable Pathways database at https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=40 .

1.b. ENERGY SECTOR

The Baseline Scenario A for 2010-2100 shows the supply trajectory of eight primary energy resources: coal, oil, natural gas, nuclear, solar, wind, hydro and biomass. The Baseline scenario from 2100 through 2400 is simply the 2100 primary energy portfolio and its levels of supply extended unchanged through 2400. See Figure 8**.**

We estimate carbon intensity τ_i ($GtCO_2/EJ$) for each primary energy resource *i (1,8)*. See *ATTACHMENT D.5-B – MODEL, Tab D.1 params – energy.* Carbon emissions M_i ($GtCO_2$) associated with energy use E_i (EJ/y) generated by energy resource *i* at any time *t* are:

$$(1) \qquad M_{i,t} = \tau_i E_{i,t}$$

Total carbon emissions *M* at time *t* are the sum of CO_2 emissions from *coal, oil, natural gas* and *biomass* at time *t*:

$$(2) \qquad M_t = \sum_1^4 M_{i,t}$$

Non-CO_2 greenhouse gases are represented by an exogenous factor; see equation (8) below.

The Baseline Scenario A trajectory of energy use E_i for each energy resource *i* over the period 2010-2100 follows that shown in IIASA SSP-2-60. Total primary energy use *E* at any time *t* is kept constant at 1185 EJ/y over the period 2100-2400, but the share contributed by each primary energy resource *i* is varied to create the four core scenarios A, B, C and D.

Recoverable stock $S_{i,t}$ (EJ) of each of the four non-renewable energy resources *coal, oil, natural gas* and *nuclear* is depleted over time:

$$(3) \qquad S_{i,t} = S_{i,t-1} - E_{i,t}$$

For data sets and estimates of ultimately recoverable energy stocks see *ATTACHMENT D.5-C – DATA, Tab A. Stocks.*

Land area *L* used for solar, wind and biomass energy in each scenario is tracked using:

$$(4) \qquad L_{i,t} = H_i \left(\frac{1}{K_i}\right) E_{i,t}$$

Where:
$L_{i,t}$ = Land area needed to support a given capacity for energy source *i* at time *t* (Ha)
$E_{i,t}$ = Energy generated by energy source *i* at time *t* (EJ/y)
K_i = Capacity factor for energy source *i* (% actual production of theoretical total; here assumed constant over time)
H_i = Conversion factor*:* land area needed per unit of energy capacity (Ha/GW)

See *D.5-B – MODEL, Tab A.1 graphics display*, Table 5, Figures 21-23, Figure 27, and *Tab D.1 params-energy.*

1.c. ATMOSPHERE AND CLIMATE SECTOR

CO_2 emissions circulate within the atmosphere, are absorbed into and circulate among the earth's oceans and terrestrial carbon reservoirs, and a portion of these absorbed emissions are recycled back into the atmosphere. We use the five-box MiniFUND model developed by Tol and Anthoff (2019) to determine atmospheric **CO2 concentration** at any time *t*:

$$Box_{i,t} = \rho_i Box_{i,t-1} + 0.000471\alpha_i M_t \tag{5}$$

where α_i denotes the fraction of emissions M (in million metric tons of carbon) that is allocated to Box_i and ρ_i denotes the rates at which carbon leaves each box, with

$$\rho_i = exp(\frac{-1}{lifetimes_i}) \tag{6}$$

We show α_i = .30, .26, .25, .15 and .04, and we show corresponding $lifetimes_l$ = 1,000,000, 363, 74, 17 and 2 years. With these values, for example, 30% of total emissions remains in the atmosphere for 1,000,000 years, while 4% is, on average, removed in 2 years. The factor 0.00047 converts Mt to ppmv.

In MiniFUND the five boxes are computational conveniences and correspond only roughly to real world carbon reservoirs. In more sophisticated models they would correspond more empirically to such carbon sinks as the atmosphere, ocean surface layer, deep ocean, terrestrial biota and oceanic biota. See *ATTACHMENT D.5-B – MODEL, Tab D.2 params-atmos* for additional background.

Total atmospheric CO2 concentration at any point in time is thus:

$$C_t = \sum_{i=1}^{5} \alpha_i Box_{i,t} \tag{7}$$

Radiative Forcing follows the conventional formula:

$$RF_t = 5.35\, ln\left(\frac{C_t}{275}\right) + EX \tag{8}$$

where 275 ppmv is the pre-industrial concentration of CO_2 and EX is the exogenous forcing of all non-CO2 greenhouse gases (largely CH_4, N_2O and SF_6). In his DICE model Nordhaus (2013) shows exogenous forcing rising from 0.25 W/m^2 in 2010 to 0.70 W/m^2 in terminal year 2100, and in his RICE model (2010) rising from 0.012 W/m^2 in 2015 to 0.30 W/m^2 in 2100 and remaining at that value for the following 490 years. For simplicity we show exogenous forcing constant at 0.30 throughout the exercise.

Global Mean Surface Warming above pre-industrial levels is:

$$T_t = \left(1 - \frac{1}{\varphi}\right) T_{t-1} + \frac{1}{\varphi} \frac{CS}{5.35\, ln2} RF_t \tag{9}$$

where *CS* is climate sensitivity, set at 3.1˚C. φ is the e-folding time and is set to

$$\varphi = \max(a + \beta^l CS + \beta^q CS^2, 1) \tag{10}$$

where α is -42.7, β^l is 29.1 and β^q is set at .001. For a climate sensitivity of 3.1 these values give an estimated e-folding time of 47.52 years.

1.d. SEA LEVEL RISE

Sea level rise, like temperature anomaly, is geometric with an equilibrium level determined by the temperature *T* and a life-time of 500 years:

$$(11) \qquad S_t = \left(1 - \frac{1}{\rho}\right) S_{t-1} + \gamma \, \frac{1}{\rho} \, T_t$$

where $\rho = 500$ is the e-folding time and $\gamma = 2$ is sea level sensitivity to temperature. The FUND sea level rise function is calibrated to match responses from general circulation models in Houghton et al. (1996).

1.e. CARBON CAPTURE AND SEQUESTATION (CCS)

The model includes two forms of CCS, *emissions capture* and *stock capture.* For both of these it allows exogenously specified *moderate* and *ambitious* policy scenarios to be applied to the two core Scenarios C and D. Emissions capture is modeled at an aggregate level and not by particular emissions source. Net emissions after emissions capture EC_t is shown as:

$$(12) \qquad M_{NET,t} = M_t - EC_t$$

Stock capture is necessarily modeled as an aggregate value:

$$(13) \qquad Q_{NET,t} = Q_t - SC_t$$

After a quantity of CO_2 is removed from the ambient air the net remaining carbon stock is redistributed among the five boxes using once more equation (5) above, in turn generating post-capture values for total atmospheric concentration, radiative forcing, warming and sea level rise.

1.f. STRATOSPHERIC AEROSOL INJECTION (SAI)

Results for SAI are treated here as a simple percentage reduction of radiative forcing:

$$(14) \qquad RRF_t = (1 - \theta_t) RF_t$$

where θ_t is the percentage by which RF_t is to be reduced in any given year.

Smith (2020) figures that 1 Tg (10^6 metric tons) of sulfate aerosol *SA* properly injected over the course of a year will lower radiative forcing by 0.63 W/m^2. We apply this value *V* to the difference between radiative forcing in the absence of SAI *(RF)* and the reduced radiative forcing *(RRF)* we wish to generate via SAI to estimate the quantity of sulfate aerosol that would need to be lofted and injected under a given scenario in any year *t*:

$$(15) \qquad SA_t = \left(\frac{1}{V}\right) (RF_t - RRF_t)$$

This is a rough result. We can get a sense, albeit even rougher, of the magnitude of any particular SAI program by calculating the number of completed jet tanker flights ("sorties") necessary to loft and inject the tons of sulfate aerosol required each year. Generalizing from Smith, we show one jet tanker lofting 20 metric tons of SO_2 payload per sortie. This delivers 10 tons S to react with atmospheric H_2O to form the active aerosol H_2SO_4. Thus:

$$(16) \qquad Sorties_t = SA_t / 10$$

See Appendix 5 for more detail on SAI.

APPENDIX 2. ENERGY RESOURCES, STOCKS AND FLOWS [This appendix is in preparation]

2.a. SPECIFICATIONS OF PRIMARY ENERGY RESOURCES TRACKED IN THIS EXERCISE

1. Coal
2. Oil
3. Natural Gas
4. Nuclear
5. Solar
6. Wind
7. Hydro
8. Biomass

The IIASA SSP-2 scenario family includes geothermal as a ninth primary energy source, but SSP-2-60 does not include it at significant levels through 2100 and so we forego it. We may use it in later work. See comment on geothermal energy in Appendix 3. Ocean energy was not included in SSP-2; we may revisit it later.

2.b. ESTIMATES OF ULTIMATELY RECOVERABLE STOCKS OF NON-RENEWABLE ENERGY RESOURCES (EJ)

1. Coal: 50,000
2. Oil: 40,000
3. Natural Gas: 200,000
4. Nuclear: 80,000

2.c. ESTIMATES OF MAXIMUM PRACTICABLE FLOWS OF RENEWABLE ENERGY RESOURCES (EJ/Y)

5. Solar: 3,000
6. Wind: 500
7. Hydro: 60
8. Biomass: 350
9. Ocean: 50 [not used in this exercise]
10. Geothermal: 1,800 [not used in this exercise]

See *ATTACHMENT D.5-C – DATA,* for the full data sets used to derive these estimates.

APPENDIX 3. SPECULATIVE SOURCES OF PRIMARY ENERGY [This appendix is in preparation]

The scenarios considered in this demonstration exercise rely on energy and energy-related technologies that are either well-established now or that we can reasonably expect can become well-established over the course of this century. Portfolios of these technologies should be able to safely power our 1185 EJ/y primary energy world for an additional three centuries, and perhaps indefinitely, with little need for post-2100 innovation.

Still, given the stakes – the future of the human community – the desirability of multiple layers of contingency preparation is obvious. Further, although the energy portfolio we've considered thus far might prove fully adequate to the task, other presently speculative energy sources, properly developed, might prove to be safer, less expensive or preferable in other regards.

We note here a number of such speculative energy technologies. They are at different stages of research and development. Many or all could turn out to be unworkable, too costly or socially unacceptable. But the consideration of scenarios extending 300 years beyond 2100 motivates us to give such technologies more than a superficial review. See additional notes in *ATTACHMENT D.5-C – DATA.*

1. *Nuclear Breeder Reactors*
Fission of U-235 emits neutrons that are absorbed by and transmute a surrounding blanket of non-fissionable U-238 into highly fissionable Pu-239. Heat from Pu-239 fission drives a steam turbine that generates electricity. Estimated accessible stocks of U-235 and U-238 could generate 2000 EJ/y for 300,000-800,000 yrs.

2. *Nuclear Fusion Reactors*
Under great pressure and temperature deuterium (2H) and tritium (3H) nuclei fuse to form helium nuclei (4He) and release heat, which can drive a steam turbine to generate electricity. 2H and 3H obtained from seawater could generate 2000 EJ/y for > 5 billion years, i.e., the time we have until our Sun expands and then collapses.

3. *Solar Hydrogen*
PV solar hydrogen dissociates seawater into O_2 and H_2 via electrolysis. The H_2 could be used to power fuel cells in vehicles, for process heat and as an energy store. Advocates estimate that solar hydrogen could replace today's 450 EJ/y of fossil fuels, using less than 1.0% of the world's ice-free land. See Ogden and Williams (1989).

4. *Geothermal Energy*
The heat energy of the Earth's interior can be tapped via deep wells and converted to electricity via steam turbines or used as process heat. Current deepest wells are 6 miles; 10-mile wells are considered feasible. Our review of fourteen studies suggests that geothermal alone could supply ~ 2000 EJ/y for several billion years.

5. *Rehabilitated Fossil Fuels*
In Scenario D we achieve zero fossil fuel emissions by 2170 with 230,000 EJ of coal, oil and gas left in the ground. If CCS allows fossil fuels to be used safely we could fully power our 1185 EJ/year world for another ~ 200 years, or more likely could use it together with renewable fuels in varying proportions for longer periods.

6. Oceanic and Tundrac Methane Clathrates
Methane trapped in rigid lattices of frozen water molecules is buried along continental slopes and in the tundrac necromass, and amounts to ~ 10Tt C. If this could be safely extracted, and if CCS would allow it to be safely combusted, it could fuel our 1185 EJ/y world for ~ 400 years. See Smil (2003).

Other speculative energy sources have been suggested. Possible oceanic sources include wave, tidal, thermal gradient and freshwater-saltwater gradient sources. Solar energy collected via orbiting satellites and transmitted to Earth via microwave has been proposed. The use of genetic, synthetic biology and nanotech engineering to create microbial-scale solar energy collectors and transmitters, to be ubiquitously embedded in or painted onto rooftops, vehicle tops, roads, parking lots and elsewhere, has been imagined. At this time none of these appear to hold promise as significant components of a global energy regime.

Some energy-climate integrated assessment models include what their authors call a “backstop technology.” This is an otherwise uncharacterized new technology able to safely and effectively substitute for any and all fossil fuels. Nordhaus, for example, uses a backstop technology in his DICE and RICE models. The backstop is initially too expensive to compete with fossil fuels, but as its cost decreases due to autonomous technological innovation (at 0.5%/y), and as the benefits of using non-fossil fuels increase with rising global mean temperature, the backstop becomes increasingly competitive and eventually drives CO_2 emissions to zero. It does this in 2230 in DICE and 2255 in RICE. See Nordhaus and Sztork (2013). The DICE and RICE backstop technologies are discussed further in *Attachment D.2.* of this working paper.

APPENDIX 4. TECHNOLOGIES FOR REDUCING MEAN SURFACE WARMING [This appendix is in preparation]

4a. MITIGATION – reducing the quantity of CO_2 produced.

A. Less activity that generates CO_2: consuming and doing fewer things that create or employ CO_2.
B. Greater efficiency: creating and/or employing less CO_2 per unit of things consumed or done.
C. Substitution: e.g. replacing fossil fuel with non-fossil fuel energy sources.

4b. CARBON DIOXIDE REMOVAL (CDR) – reducing CO_2 already in or about to enter the atmosphere

A. PHOTOSYNTHETIC CO2 UPTAKE; STORAGE IN BIOMASS

1. Large-scale afforestation, reforestation and some forms of curtailed deforestation
2. Biochar production and burial
3. Soil carbon enrichment
4. Ocean iron fertilization (OIF)
5. Improved agricultural, forestry & coastal management practices

B. MECHANICAL AND CHEMICAL CO2 UPTAKE; SEQUESTRATION MOSTLY UNDERGROUND

a. Point Source Capture (aka emissions capture)

6. Point-source capture after fossil fuel combustion (point-source CCS)
7. Point-source capture after biomass combustion (BECCS; hybrid w photosynthetic uptake)

b. Direct Air Capture

8. Direct air capture with active air forcing; chemical uptake (DACCS)
9. Direct air capture with passive air contact; chemical uptake
10. Enhanced weathering of silicate rock surfaces; passive air contact, some chemical catalyst uptake

4c. RADIATIVE FORCING MANAGEMENT (RFM)

A. Solar radiation management (SRM) - to increase solar radiation reflected back into space.

11. Surface-based albedo modification (SAM)
12. Marine sky brightening (MSB)
13. Stratospheric aerosol injection (SAI)
14. Orbital space mirrors (OSM)

B. Increasing the amount of terrestrial long wave radiation that escapes into space

15. Cirrus cloud thinning (CCT)

Notes:

* This taxonomy draws on Reynolds (2019), Lawrence et al. (2018), Fuss et al. (2018) and EASAC (2018), among others.

* The numerous particular technologies and policies of 4a. Mitigation are not noted here, as this demonstration exercise lumps their combined impact into the single measure of reductions in fossil fuel use. But mitigation is indeed the primary and most important means of reducing mean surface warming.

* Item 4b.B.7, BECCS, is a hybrid technology. It uptakes CO_2 via photosynthesis but its capture, transport and storage systems are those of point-source CCS.

* Early on the term *geoengineering* was used to include both CDR and RFM, but now more often means RFM plus Ocean Iron Fertilization (OIF) and other exotic techniques. *Radiative forcing management* and *solar geoengineering* are near synonyms. The category of *Mitigation* is often interpreted as including CCS but *not* BECCS. Taxonomies differ in the criteria they use for classification in different contexts and no one taxonomy can or need be taken as definitive.

APPENDIX 5. SPECULATIVE GEOENGINEERING TECHNOLOGIES

5.a. INTRODUCTION

If it turns out to be difficult to generate desired levels of non-fossil fuel energy, or if CCS proves to be prohibitively problematic at scale, or if the speculative energy sources noted in Appendix 3 are not available or are unacceptable, technologies often called *geoengineering* might be considered. These include:

1. Radiative Forcing Management (RFM) to block incoming radiant energy and unblock the escape of heat energy:
    * Surface-based albedo modification (e.g. of deserts, ice fields, ocean surface, roof-tops, roads etc.)
    * Tropospheric marine sky brightening via flotillas of large water-cannon spray vessels
    * Stratospheric aerosol injection (SAI) of sulfate aerosols ($S0_2$, H_2S, H_2SO_4) or other aerosols
    * Low earth orbit adjustable reflecting mirrors (many small ones or a few very large ones)
    * Cirrus cloud thinning (CCT) to increase the escape of terrestrial long wave radiation

2. Ocean iron fertilization. This is a form of CCS but is often included with geoengineering approaches.

3. Solutions involving synthetic biology, genetic engineering, nanotechnology and other emerging technologies.

On the basis of current knowledge most geoengineering technologies are considered highly problematic. Most of the technologies noted in Appendix 4b involve *removal* of undesirable substances, notably CO_2, from the atmosphere, whereas the technologies noted here and in Appendix 4c involve the dispersal of potentially problematic substances or objects *into* the Earth's environment, generally over very large areas and in some cases the entire planet, albeit for intended helpful purposes. They vary greatly in the profile and uncertainty of their cooling effects, regional impacts, residence times and ease of deactivation or removal. See reviews by Dunne (2018), Lawrence et al. (2018), Saeed et al. (2018) and Wetter and Zundel (2018). Many authors who are cautiously open to some forms of RFM emphasize their role as one-time supplements rather than as substitutes for mitigation and carbon removal. See Boucher et al. (2013), Smith and Rasch (2012) and Wigley (2006).

5.b. PROPOSALS FOR STRATOSPHERIC AEROSOL INJECTION

The RFM proposal that has received the most attention to date is that of ***stratospheric aerosol injection (SAI).*** It involves injection of large quantities of sulfur dioxide (SO_2) or other aerosol precursors into the lower stratosphere. These sulphates react with water vapor to form a fine mist of sulfuric acid (H_2SO_4), which scatters incoming radiant energy and thus cools the atmosphere and the Earth's surface. Volcanic eruptions that eject sulfate aerosols into the stratosphere have this cooling effect. A cap on warming of 2.0˚C or any other value might be established by injecting quantities of aerosol just sufficient to offset the warming generated by continuing CO_2 emissions. Proposed scenarios foresee large jet tanker aircraft operating year-round to create and maintain the reflective layer of aerosols. Aerosol residence time in the stratosphere is 1-3 years, so the injection process would need to be continuous. The lifecycle costs of SAI are generally thought to be significantly lower than comparable mitigation and CCS interventions. See Larson (2016), Keith and MacMartin (2015) and Keith (2013) for sympathetic accounts of SAI.

SAI poses profound risks. If at some point during the many-decadal span of a typical SAI intervention the program were for any reason abruptly halted, the world would experience ***termination shock,*** a sharp increase in warming as the impact of the high CO_2 concentration that built up during the period of SAI masking is suddenly unleashed. Warming could rise in a matter of months to levels otherwise to be expected only over decades. See Goes et al. (2011), Brovkin et al. (2008) and Matthews and Caldeira (2007). **[1]** Although SAI, if successful, might serve as a temporary palliative for undesired warming, it does little to reduce the on-going acidification of the world's oceans as the atmospheric build-up of CO_2 is absorbed into the ocean surface layers, with negative impact on primary productivity and sensitive habitats such as coral reefs. See Lauvset et al. (2017). Further, studies have warned that

SAI could perturb the global hydrological cycle, perhaps affecting global and regional air stream and precipitation patterns including those of the Asian and African monsoons. See Robock (2009) and Bala et al. (2008). Some model simulations suggest that SAI cooling would be less effective in the high latitudes and thus would do little to prevent the ultimate collapse of the Antarctic and Greenland ice sheets. Although many agricultural crops would benefit from the lesser warming, that benefit could be offset by reduced sunlight and rainfall. The reduction in incident sunlight could reduce the efficiency of PV solar power systems and thereby impede their necessary build-out. SAI could affect atmospheric chemistry in a manner that would slow the process now underway that is closing the Arctic and Antarctic ozone holes. See Tjiputra et al. (2015) and Robock (2014). **[2]** Svoboda et al. (2011) argue that SAI has the clear potential to violate seriously important and widely shared ethical and moral criteria of justice, and that the burden rests with its advocates to show that it will not. There is in addition the danger that even the mere discussion of the possible beneficial potential of SAI could generate a moral hazard, as people come to imagine the downstream use of SAI as a technological fix that obviates the need for difficult near-term reductions in CO_2 emissions by current generations, thus unfairly imposing risk of harm on future generations. **[3]**

The question SAI governance could prove intractable. Who would decide whether or not to initiate an SAI intervention, to what degree, for how long, and using what technology? Who would pay for it? Who would ensure against accidental or malicious abrupt termination? In general, authors who doubt the wisdom of SAI in the first place regard the complications of governance as simply another argument against the practice and see little value in debating the merits of alternative governance approaches. By contrast, authors sympathetic to SAI go to great lengths to carefully consider the pros and cons of a wide range of modes of governance. It's difficult to argue that such research should not be done, yet it's well known that the production of such research can have the effect of normalizing and legitimizing a technological intervention that many would otherwise reject. For discussion of solar geoengineering governance see Reynolds (2020, 2019a, 2019b) and Grieger et al. (2019).

Despite or because of these many concerns, some analysts have begun exploring a range of SAI proposals in detail. We describe and model one such proposal in the section following.

5.c. A SCENARIO EXERCISE: STRATOSPHERIC AEROSOL INJECTION

Suppose that all possible mitigation options and CCS technologies are being employed at the most ambitious levels possible, and that we still face a degree and duration of warming which, while probably survivable, is nonetheless highly destructive of many social, economic, environmental and other values. It might be argued that this is the situation we face at the conclusion of our demonstration exercise. We are fated to live with warming above 2.0˚C for 115 years, with a peak at 2.4˚C in 2120, before returning to below 2.0˚C in 2190. Suppose in addition there is reason to believe that a warming of, say, 2.7˚C could trigger a massively destructive, perhaps globally catastrophic, climate-related disruption. And further, that while the odds that this catastrophe might be trigged at 2.4˚C may be small, they remain greater than zero given the inherent uncertainty of the climate system. Under these conditions it might be argued that a time-limited use of SAI to keep warming from exceeding, say, 2.2˚C could be justified. It would greatly reduce predictable loss and damage and would provide a safer margin against possible catastrophe.

Figures 38-43, Table 7 and **TABLE A** show how SAI might work in such a situation. We draw on Smith (2020) for technical specifics; see **BOX A** below. In 2050 high-altitude jet tanker aircraft designed to most effectively disperse sulfate aerosols initiate the SAI intervention. It begins modestly but ramps up each year. Large quantities of SO_2 are injected at ~ 60,000 feet on both sides of the equator, where they react with water vapor to form H_2SO_4 aerosol. Steady stratospheric pole-ward currents spread the aerosol evenly throughout the northern and southern hemispheres. The negative radiative forcing of the aerosol keeps warming from exceeding 2.2˚C. Meanwhile our ambitious CO_2 mitigation and CCS initiatives continue to slow and eventually reverse the growth of atmospheric CO_2 concentration. Warming declines from its 2110 peak of 2.2˚C and by 2170 drops below 2.0˚C. At that point the aerosol injections, which have been tapering off as warming has declined, successfully conclude. Emissions mitigation and point-source CCS end in that same year, as CO_2 emissions have finally been reduced to zero. DACCS can continue for as long as the human community believes is warranted. If it continues for another 70 years, i.e. through 2240, surface warming will have dropped to below 1.5˚C.

To summarize: In 2080 the world passes the 2.0˚C mark and begins a 90-year period of exceptional trial. For the first 30 years the atmosphere warms to its 2110 peak of 2.2˚C. Over the remaining 60 years warming steadily declines, returning to below 2.0˚C in 2170. This excursion-and-return requires maximally ambitious mitigation and CCS commitments along with a high-risk program of SAI during the 120-year period 2050-2170.

What if the human community believes that the costs and risks of a 2.2˚C warming are in fact too great, and desires instead to avoid exceeding the 2.0˚C ceiling as affirmed in the 2015 Paris Agreement? In that case we begin our SAI intervention again in 2050 but increase aerosol injections to twice the level used in the first scenario, and do so more rapidly. Warming peaks in 2100 at 2.0˚C and declines after that. This scenario requires the same maximally ambitious mitigation and CCS commitments as before, and a stronger, longer and thus riskier program of SAI during the 150-year period 2050-2200.

Some sense of the scale of these moderate and maximal SAI policy scenarios can be seen in **Figures 42-43**. In its peak year 2100 the moderate SAI program injects 720,000 metric tons of SO_2 aerosol into the stratosphere in the course of nearly 72,000 air tanker sorties. In the same peak year 2100 the maximal SAI program injects 1,440,000 tons SO_2 using nearly 144,000 sorties. Using Smith's estimates in which each tanker makes five sorties/day on each of 330 days/year gives us a required fleet for the maximal SAI program of 87 or ~ 100 large jet tankers. This compares with the current fleets of ~ 900 aircraft flown by American Airlines and ~ 5,000 flown by the U.S. Air Force.

- - - - - - - -

BOX A. Treatment of technical details regarding the SAI scenarios

In the scenarios proposed by Smith (2020) fleets of jet tankers carry highly compressed $S0_2$ into the stratosphere, where it is injected and quickly oxidizes with water vapor into the active sulfate aerosol H_2SO_4. Smith pegs the negative impact of the aerosol on radiative forcing to be -0.63 W/m^2 for each Tg-S injected in the course of a year. Each tanker carries 15.7 tons of SO_2 payload. With these values we can calculate the amount of SO_2 needed to generate the negative radiative forcing required by our moderate and maximal SAI scenarios shown in Figure 38 and the number of jet tanker sorties necessary to carry that quantity of SO_2 into the stratosphere.

The major intent of Smith's study is to generate estimates of the total costs of various SAI scenarios, which governments and potential investors understandably need to know. Towards this end Smith goes into considerable engineering and operational detail. He suggests that after ~ 25 years the initial $SO_2 \Rightarrow H_2SO_4$ aerosol is supplanted by an otherwise unidentified "Aerosol-2" that is 33% more effective at countering radiative forcing. He suggests as well that over a ~ 70 year span the jet tanker aircraft go through three generations of design improvements, each offering greater payload capacity and lower operating costs; e.g. the third generation has 62% greater payload capacity and may be crewless drones. Smith notes that sulfate aerosols tend to clump together at increasing rates with increasing dispersion densities, and that larger particles are both less efficient at negative radiative forcing and drop out of the stratosphere more rapidly. To incorporate this functional degradation into his model he shows the aerosol negative radiative forcing value decreasing by 1% for every additional Tg-S of aerosol dispersed. These several dynamic values are easy to incorporate into our spreadsheet model but the differences they make in our final results are not large, and to include them in our very general and speculative model would display a misleading precision. For simplicity we've kept the aerosol at its initial negative forcing value throughout the scenario lifetimes, and we use a single mid-range tanker payload of 20 tons SO_2 throughout. We don't need to worry about the sulfate-clumping problem because even our maximal SAI scenario disperses only 3.2 Mt-SO_2/y. This is quite modest compared to most of Smith's nine scenarios, the most ambitious of which calls for 30 Mt SO_2 to be injected each year by 900 aircraft on 1 million sorties. The major reason for this difference is that we show SAI used only in conjunction with ambitious mitigation and CCS policies, while in Smith's scenarios SAI is used in place of such policies.

APPENDIX 6. UNCERTAINTY, CLIMATE SENSITIVITY AND POLICY

The earth's climate is the product of a complex system involving the atmosphere, hydrosphere, land and sea biota, geodynamics, solar activity, human activity and more. It is difficult to forecast levels and rates of climate change, intensities and distribution of damages, and the efficacy of proposed policies with the degrees of precision and confidence that policy makers and the public understandably desire. Here we illustrate ways in which uncertainty regarding the earth's climate system might influence the results generated by our long-run energy-climate model.

6.a. CLIMATE SENSITIVITY

One of the most important uncertain climate parameters used in integrated assessment models is that of *climate sensitivity.* It's conventionally defined as the rise in global mean surface temperature resulting from a doubling of the concentration of carbon dioxide over pre-industrial levels after major feedback dynamics have worked their way through the climate system. [1] Climate sensitivity is used in our model in Equation (9), which shows the rise in global mean surface temperature as a function of radiative forcing. The greater the value of climate sensitivity *CS*, the greater the warming generated by any given level of radiative forcing.

The immediate impact of an increase in CO_2 concentration on surface warming is relatively well understood and easy to compute, but the dynamics of global and regional feedbacks set into play by this warming are not. The melting of snow cover and ice, the growth or die-back of large swaths of vegetation, and the formation of different sorts and patterns of cloud systems can change the earth's ability to reflect radiant energy and retain heat energy in ways that can reinforce or counter any initial change in surface temperature. Warming increases the atmosphere's ability to hold water vapor, which itself is an important greenhouse gas. The rates at which the oceans can absorb heart energy and molecular CO_2 change as ocean temperatures and CO_2 concentrations change. These and other feedback mechanisms are still poorly understood, and climate sensitivity remains a particularly uncertain parameter. For more on climate sensitivity see IPCC AR5 Technical Summary (2013). [2]

In its first Assessment Report (AR1, 1990), the IPCC estimated with 66% confidence that climate sensitivity falls within a range of 1.5– 4.5°C. This estimate has remained largely unchanged in the reports that have followed. AR4 (2007) reported a "best estimate of about 3 °C". In his 2010 RICE model Nordhaus set climate sensitivity at 3.2 °C, and in the most recent version of DICE (2016) he set sensitivity at 3.1 °C. For their MiniFUND model Tol and Anthoff (2019) set climate sensitivity at 3.0 °C. For a review of past climate sensitivity estimates see Hausfather (2018). [3] [4]

Recent studies suggest that the forthcoming IPCC AR6 (set for release over June-October 2021) might include adjustments in the climate sensitivity parameter. Zelinka et al. (2020) report that climate sensitivity values generated by the latest Coupled Model Intercomparison Project (CMIP6) models span a range of 1.8 °C – 5.6 °C, with a central estimate of ~ 3.9 °C. Sherwood et al. (2020) report a narrower range and lower upper value, suggesting with 66% confidence that climate sensitivity lies within 2.6–3.9 °C. Nijsse et al. (2020), using post-1975 temperature change and CO_2 concentration records together with data used in CIMP6, report a markedly lower range of 1.9–3.4 °C, suggesting a central estimate of ~ 2.6 °C. Climate sensitivity is clearly an uncertain parameter.

6.b. AN EXERCISE

Thus far in our demonstration exercise we've used a climate sensitivity value of 3.1°C. As noted in *ATTACHMENT D.5-B – MODEL, Tab D.2 params–atmos,* this is the current IPCC AR5 central estimate of 3.0 °C raised by 0.1°C (3.3%) to incorporate a modicum of precaution.

To test the sensitivity of the energy-climate model used in this exercise to the value of the climate sensitivity parameter we use the current IPCC AR5 range of 1.5-4.5°C, with two modifications. First we narrow the range to 2.0– 4.0 °C so as to generate trajectories somewhat more statistically likely to be realized in the real world [5].

Then we increase these lower and upper values by 0.1˚C (5% and 2.5% respectively) as we did with the central estimate, again to incorporate precaution.

Table AA and **Figure AA** show the trajectory of Baseline warming that our demonstration model generates using these upper, central and lower values of climate sensitivity. We see that even this somewhat compressed range of CS values has a significant impact on the trajectory of Baseline warming.

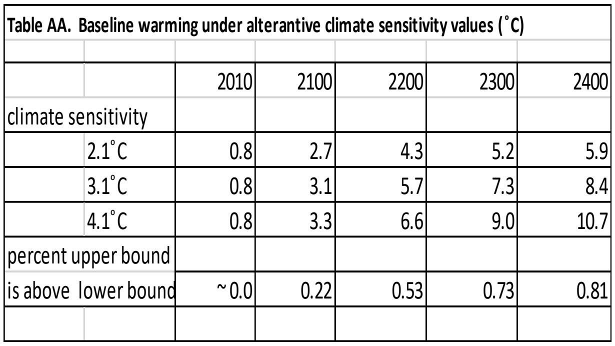

Table AA. Baseline warming under alterantive climate sensitivity values (˚C)

		2010	2100	2200	2300	2400
climate sensitivity						
	2.1˚C	0.8	2.7	4.3	5.2	5.9
	3.1˚C	0.8	3.1	5.7	7.3	8.4
	4.1˚C	0.8	3.3	6.6	9.0	10.7
percent upper bound						
is above lower bound		~0.0	0.22	0.53	0.73	0.81

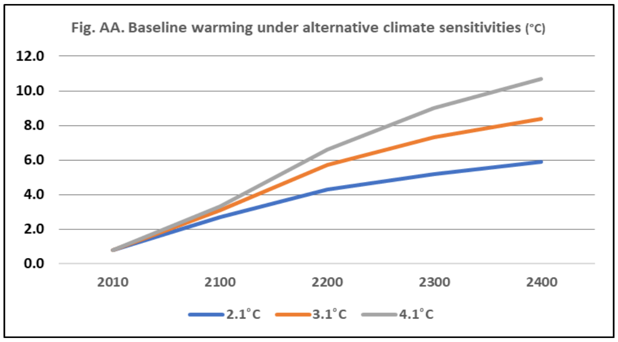

Fig. AA. Baseline warming under alternative climate sensitivities (˚C)

Table AB shows how our previously identified Scenario D, with and without selected CCS and SAI policies, varies with upper, central and lower climate sensitivity values. If climate sensitivity is close to 4.1˚C our situation is dire and our options limited. Our previously identified maximum policy regime, using maximally ambitious mitigation, CCS and SAI, now leaves us with warming peaking at 2.3˚C over the period 2100-2180 and not returning to below 2.0˚C until 2230. If that level and duration of warming were judged to be unacceptable, the only option readily at hand would be an *augmented* maximum SAI in which stratospheric sulfate injections reach 2,262,000 metric tons S in 2100, a nearly 60% increase over the previous maximum. Note that every additional ton of injected sulfate increases the likely intensity of any terminal shock that would follow a sharp disruption of SAI operations.

If climate sensitivity is close to 2.1˚C our situation is far more manageable. We would still need ambitious mitigation and emissions CCS to keep warming from exceeding 2.0˚C and to curtail ocean acidification. But we would need only moderate DACCS and we would have no need of SAI at all. [6]

The results shown in Table AB suggest what might be considered a workable, common sense climate policy strategy. Whatever value climate sensitivity turns out to have, we will need maximally ambitious mitigation and emissions CCS policies and at least a moderate level of stock capture CCS. We need to build global consensus around these measures and their rapid implementation. If and when it appears that we might be facing conditions of higher climate sensitivity, or if our mitigation and CCS efforts are lagging, we will need to ramp up to maximally ambitious stock CCS. So even if there's a chance that we won't need it at all, we should proceed as if we do, so that if in fact we need it we're not caught flat-footed on development and deployment. If it subsequently appears that we are facing still higher climate sensitivity, we can decide whether or not to employ SAI. Fortunately, SAI doesn't require extensive lead time to become operational. We would need to be prepared for its use, but we would not have to put it in play until we are certain that we need and want to do so. [7]

Of course, our real-world experience is unlikely to be this straightforward. We can't assume that more research will allow us to hone in on the "true" value of climate sensitivity, because complex systems are often inherently undetermined. Even if we can significantly narrow the range of the climate sensitivity parameter, there's no assurance that we can do so within a time frame that would allow that information to be usefully applied. Further, there's no reason to believe that climate sensitivity remains constant over time, as we imply when we apply a single value such as 3.1˚C over a period of 300 years. And there are scores of uncertainties other than climate sensitivity that importantly bear on our prospects for effectively addressing climate change. The scales of space and time over which we are operating ensure that many climate policy decisions will necessarily involve large elements of faith, hope and precaution. [8]

TABLE AB. GLOBAL MEAN SURFACE WARMING UNDER ALTERNATIVE SCENARIOS AND CLIMATE SENSITIVITY ESTIMATES

		A	B	C	D	E	F	G	H	I	J
	SCENARIO D: ACCELERATED MOSTLY SOLAR	**first year > 2.0˚C**	**peak warming (˚C)**	**year(s) of peak warming**	**year returning to ≤ 2.0˚C**	**year SAI begins**	**year SAI ends**	**total years > 2.0˚C**	**total years of SAI**	**aerosols injected in maximum SAI year (tons S)**	**total sorties needed in max SAI year**
2	***MITIGATION ONLY***										
	Upper bound CS (= 4.1)	2070	3.4	2170 (2170-2180)	~ 2450	na	na	380	0	0	0
	Mid-range CS (= 3.1)	2075	2.8	2140 (2130-2170)	2300	na	na	225	0	0	0
	Lower bound CS (= 2.1)	2100	2.1	2110 (2100-2120)	2140	na	na	40	0	0	0
4	***MITIGATION + AMBITIOUS CCS***										
	Upper bound CS (= 4.1)	2070	2.8	2140 (2120-2160)	2250	na	na	180	0	0	0
	Mid-range CS (= 3.1)	2075	2.4	2120 (2100-2140)	2190	na	na	115	0	0	0
	Lower bound CS (= 2.1)*	never	1.9	2090 (2090-2100)	always ≤ 2.0˚C	na	na	0	0	0	0
	MITIGATION + AMBITIOUS CCS + SAI										
5	**+ Moderate SAI**										
	Upper bound CS (= 4.1)	2070	2.6	2140 (2130-2160)	2250	2050	2170	180	120	720,000	72,000
	Mid-range CS (= 3.1)	2080	2.2	2110 (2100-2130)	2170	2050	2170	90	120	720,000	72,000
	Lower bound CS (= 2.1)	SAI would not be necessary if CS = 2.1									
6	**+ Maximum SAI**										
	Upper bound CS (= 4.1)	2080	2.3	2140 (2100-2180)	2230	2050	2200	150	150	1,440,000	144,000
	Mid-range CS (= 3.1)	never	2.0	2100 (2080-2110)	always ≤ 2.0˚C	2050	2200	0	150	1,440,000	144,000
	Lower bound CS (= 2.1)	SAI would not be necessary if CS = 2.1									
7	**+ Augmented Maximum SAI to ensure 2.0˚C ceiling if CS = 4.1**	never	2.0	2100 (2080-2210)	always ≤ 2.0˚C	2050	2200	0	150	2,262,000	226,000
	* If CS = 2.1 a peak very near 2.0˚C could be achieved with only moderate emisions CCS and with no stock CCS:	2110	2.05	2110 (2110-2110)	2120	na	na	~ 10	0	0	0

Columns

Columns A-H are as noted for Table A (p10). Column I shows the amount of stratospheric aerosol to be injected in the year of maximum application. Column J shows the number of jet tanker flights needed to deliver that payload. Figures 42 and 43 (B-Model Tab A) show the full schedule of injections and sorties.

Note

1. The numbering system 1-7 for the scenarios applies to this Table, to Table A (p 10) and to Table G.2-2 (p 39), but is not used elsewhere in this exercise.
2. As in Table A, "ambitious CCS" means the use of ambitious emissions CCS and ambitious DACCS, together, as shown in B-Model Tab A, Figure 25.

APPENDIX 7. POPULATION AND CLIMATE CHANGE

In the energy-climate model used in this demonstration exercise the trajectory of population over the period 2010-2400 is fixed as shown in *ATTACHMENT D.5-B – MODEL, Tab A Figure 1*. Population grows to 9.5 billion by 2080 and remains at that level thereafter. Similar peak-and-stabilize population trajectories characterize many of the most influential global energy-climate models prepared in recent decades. As noted in DN 54, however, demographers increasingly suggest that the world total fertility rate (TFR) might in fact decline to below the replacement TFR of 2.1 children/woman well before the end of this century and remain there for quite some time. In that case world population could decline dramatically over the course of this century and into the next. How might such scenarios of population decline affect the challenges posed by climate change?

Figure C, taken from *ATTACHMENT D.5-B – MODEL Tab G.2*, shows three stylized long-run population trajectories. Trajectory A is the peak-and-stabilize trajectory just described and used thus far throughout this exercise. With Trajectory B population peaks at 8.8 billion in 2060 and then declines to and stabilizes at 4.25 billion. With Trajectory C population peaks at 8.3 billion in 2050 and then declines to and stabilizes at 2.5 billion. Data and procedures used to construct Trajectories B and C are shown in *ATTACHMENT D.5-B – MODEL Tab G.1.*

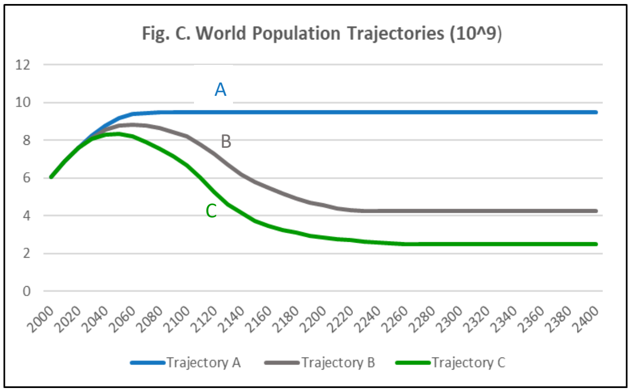
Fig. C. World Population Trajectories (10^9)

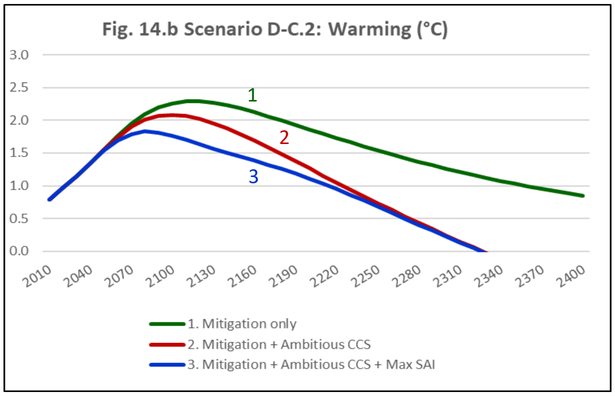
Fig. 14.b Scenario D-C.2: Warming (°C)

We applied the new population decline trajectories B and C to our four core primary energy use scenarios A, B, C and D to generate ten new energy-population scenarios. We selected four of the most ambitious of these to run through our full energy-climate model under varying policies regarding mitigation, CCS and SAI. **Table G.2-2** (p 39) shows selected results. See *D.5-B – MODEL Tabs G.1-G.2* for the full model exercise, results and discussion.

Figure 14.b (above), taken from *D.5-B – MODEL Tab G.2*, compares trajectories of warming generated by the most ambitious of our original primary energy scenarios, Scenario D, under alternative policy scenarios involving mitigation, CSS and SAI, but now assuming a) that population follows Trajectory C, and b) that the “surplus” solar and wind capacity now available due to population decline is used to accelerate the retirement of fossil fuels and nuclear energy. This configuration allows us to limit warming to a peak of 1.9˚C with recourse to only moderate SAI, or to 2.1˚C with no need for SAI at all. In the latter case warming would exceed 2.0˚C for the comparatively short period of 30 years. Other options for keeping warming close to or below 2.0˚C become available as well under scenarios involving population decline.

It’s important to acknowledge that the topic of population and the environment has a bad history. Much advocacy of “population control,” from the late 19th century to the present, has been motivated by racist, classist and eugenicist values and beliefs. Although the demographers now anticipating global population decline attribute this decline largely to personal choice as education, urbanization, economic security and access to health care expand, rather than to pro-active policies of population control, causation is complex and different communities will inevitably be impacted in different ways. The possibility of conflict remains high and any discussion involving population and the environment needs to deal with it.

TABLE G.2-2. GLOBAL MEAN SURFACE WARMING UNDER SELECTED ENERGY-POPULATION SCENARIOS

Energy Scenario D: Accelerated Mostly Solar

Population Trajectory A: Population peaks and stabilizes at 9.5 billion in 2080.

Population Trajectory B: Population peaks at 8.8 billion in 2060, declines to and stabilizes at 4.25 billion by 2230.

Population Trajectory C: Population peaks at 8.3 billion in 2050, declines to and stabilizes at 2.50 billion by 2260.

Population-Energy Scenario D-C.2 : Population Trajectory C + Energy Scenario D, with "surplus" renewable energy capacity available as population declines used for earlier retirement of fossil fuels and nukes.

		A	B	C	D	E	F	G	H	I	J
	ENERGY SCENARIO D: ACCELERATED MOSTLY SOLAR	first year > 2.0˚C	peak warming (˚C)	year(s) of peak warming	year returning to ≤ 2.0˚C	year SAI begins	year SAI ends	total years > 2.0˚C	total years of SAI	aerosols injected in maximum SAI year (tons S)	total sorties needed in max SAI year
2	***MITIGATION ONLY***										
	Population Trajectory A	2075	2.8	2150 (2130-2170)	2300	na	na	225	0	0	0
	Population Trajectory B	2080	2.7	2140 (2130-2150)	2270	na	na	190	0	0	0
	Population Trajectory C	2080	2.5	2130 (2110-2160)	2240	na	na	160	0	0	0
	Population-Energy Scenario D-C.2	**2080**	**2.3**	**2120 (2100-2130)**	**2180**	na	na	**100**	0	0	0
4	***MITIGATION + AMBITIOUS CCS***										
	Population Trajectory A	2075	2.4	2120 (2100-2140)	2190	na	na	115	0	0	0
	Population Trajectory B	2080	2.3	2110 (2100-2130)	2170	na	na	90	0	0	0
	Population Trajectory C	2080	2.2	2100 (2090-2130)	2150	na	na	70	0	0	0
	Population-Energy Scenario D-C.2	**2090**	**2.1**	**2100 (2090-2110)**	**2120**	na	na	**30**	0	0	0
	MITIGATION + AMBITIOUS CCS + SAI										
5	**+ Moderate SAI**										
	Population Trajectory A	2080	2.2	2110 (2100-2130)	2170	2050	2170	90	120	720,000	72,000
	Population Trajectory B	2090	2.1	2110 (2090-2130)	2160	2050	2170	70	120	681,000	68,000
	Population Trajectory C	never	2.0	2100 (2080-2130)	always ≤ 2.0˚C	2050	2170	0	120	637,000	64,000
	Population-Energy Scenario D-C.2	never	1.9	2090 (2080-2110)	always ≤ 2.0˚C	2050	2170	0	120	565,000	56,000
6	**+ Maximum SAI**										
	Population Trajectory A	never	2.0	2100 (2080-2110)	always ≤ 2.0˚C	2050	2200	0	150	1,440,000	144,000
	Population Trajectory B	never	1.9	2090 (2080-2120)	always ≤ 2.0˚C	2050	2200	0	150	1,362,000	136,000
	Population Trajectory C	never	1.9	2090 (2080-2100)	always ≤ 2.0˚C	2050	2200	0	150	1,274,000	127,000
	Population-Energy Scenario D-C.2	**never**	**1.8**	**2080 (2070-2090)**	**always ≤ 2.0˚C**	**2050**	**2200**	**0**	**150**	**1,130,000**	**113,000**

The numbers 2-6 above align the scenarios in this table with those in Table A (p 10) and Table AB (p 37).

Columns A-J are as noted for Table A and Table AB.

Comment: Alternative SAI policies might trade shorter and/or less intense, and thus less risky, deployment in exchange for somewhat longer and/or higher, and thus more risky, warming.

APPENDICES DISCUSSION NOTES

APPENDIX 5: SPECULATIVE GEOENGINEERING TECHNOLOGIES

[1] Parker and Irvine (2018) suggest that the risk posed by termination shock may be overstated in much of the current literature and might be satisfactorily minimized through fairly simple precautions. They calculate that the warming trajectory generated by sudden termination of SAI that is offsetting warming by less than 0.4˚C would not constitute a shock. By that measure the moderate SAI policy used in this exercise, which reduces warming from 2.4˚C to 2.2˚C, would not be considered to pose a danger if suddenly terminated. However, our maximum SAI policy reduces warming from 2.4˚C to 2.0˚C and so is exactly at the posited termination shock threshold. Parker and Irvine note that the most commonly mentioned potential causes of sudden SAI termination are terrorist attack and natural disaster. They argue that deployment of SAI airbases in several countries throughout the world (which in any case is needed to ensure efficient aerosol dispersal), with each host country supporting a determined excess deployment capacity, should suffice against the great majority of such threats. Still, low probability/high impact events, e.g., global nuclear war, cannot be ruled out. Parker and Irvine conclude that we should strive to address climate change in ways that don't run the risk of SAI termination shock in the first place, and that we should continue research on the risks of large SAI deployment and possible remedies.

[2] Keith et al. (2016) acknowledge that the use of sulfate aerosols for SAI could have undesirable impacts. In the process of scattering solar radiation while in the lower stratosphere these aerosols would also warm that portion of the atmosphere, which in turn would allow greater concentrations of water vapor, which is itself a greenhouse gas. The summed additional warming would reduce the level of net cooling that the aerosol is intended to generate in the first place. Further, the H_2SO_4 aerosols that are the scattering agent can react with acids of nitrogen, chlorine and bromine in the atmosphere and in turn catalyze reactions that dissociate and recombine with ozone molecules and thus degrade the ozone layer. The authors suggest as an alternative the use of **calcite ($CaCO_3$) aerosol particles**. They perform a simulation using calcite that generates negative radiative forcing of 1.0 W/m2, an *increase* in columnar ozone of 3.8%, and far less radiative stratospheric heating, than would have been generated using sulphate aerosols. Note that the maximum negative radiative forcing employed in our own demonstration exercise is 0.9 W/m2.

[3] Svoboda et al. (2011) and Svoboda et al. (2019) read like briefs for a moot court university law school exercise. The 2011 paper exhaustively catalogues the many ways in which SAI might violate widely held norms of justice, with special attention to distributive, intergenerational and procedural justice, and concludes that "… [T]he potential ethical problems with [SAI] pose serious obstacles to it being a just response to climate change." The 2019 paper adopts a central principle of justice: "If a person is especially at risk of very bad things happening due to the actions and omissions of others, that person has a *prima facie* claim to have the risk reduced." The paper reviews the many likely impacts of climate change and assesses the potential of SAI, and concludes that because climate change will impact many people adversely through no fault of their own, and because SAI is likely to reduce the risk of climate change, SAI is likely to reduce climate injustice and is worthy of further consideration.

APPENDIX 6: UNCERTAINCY, CLIMATE CHANGE AND POLICY

[1] What we're calling here *climate sensitivity* is, technically, *equilibrium* climate sensitivity, called such so as to distinguish it from *transient* climate sensitivity, which is the immediate impact of a CO_2 doubling on mean surface warming before feedbacks are taken into account.

[2] The climate sensitivity parameter isn't a constant of nature as is, say, the speed of light. It doesn't appear anywhere in the sophisticated coupled atmosphere-ocean general circulation models used by climate scientists. It's a constructed parameter arrived at after all the dynamics of a given model run have run their course, developed specifically to help those working with necessarily simplified IAMs involving CO_2-driven climate change.

There's no reason to assume that the climate sensitivity parameter remains constant as CO_2 concentrations change, as mean surface warming changes, or as we take action to limit climate change.

[3] In AR4 (2007) the IPCC raised the lower estimate from 1.5˚C to 2.0˚C, but in AR5 (2013) it restored the 1.5˚C low estimate. In AR5 the IPCC declined to offer a single best or mean estimate for climate sensitivity, citing "a lack of agreement on values across assessed lines of evidence and studies," but many researchers continued to take 3.0˚C as a central estimate.

[4] In 1979 U.S. meteorologist Jule Charney prepared a 22-page report for the National Research Council in which he noted on page 2 that "We estimate the most probable global warming for a doubling of CO_2 to be near 3°C with a probable error of ± I.5˚C." See Charney (1979). He had access to the results of new models that suggested that a doubling of CO_2 concentration might generate warming in the neighborhood of 3°C. The upper and lower bounds of ± I.5˚C, however, were little more than reasonable guesstimates. The fact that hundreds of empirical studies conducted over the ensuing forty years happen to have generated those same boundary values as findings raises questions about the research process.

[5] While climate sensitivity is somewhat more likely to fall within the range 1.5-4.5˚C than within the range 2.0-4.0˚C, values near 2.0˚C and 4.0˚C are somewhat more likely to be realized than are values near the boundary values of 1.5˚C and 4.5˚C.

[6] Greater use of DACCS could be entertained if we wished to return to 2.0˚C more rapidly and/or stabilize near or below 1.5˚C. Alternatively, if a 2.05˚C peak were acceptable we could do that with only moderate emissions capture and no DACCS at all, as noted in Table AB.

[7] This sanguine account is hardly the full story. A full treatment of warming and policy under conditions of climate sensitivity uncertainty would necessarily consider extreme and even outlier risks. The IPCC AR5 estimate showing 66% confidence that climate sensitivity falls within 1.5-4.5˚C might be taken to suggest a ~ 17% chance that sensitivity is *over* 4.5˚C, which is hardly a trivial risk. And my casual admonition to "build global consensus" echoes the naivete that characterized much global climate policy advocacy for much of the 1990s and 2000s.

[8] Many sorts of uncertainty are encountered in integrated assessment and other climate policy modeling. We can distinguish parameter uncertainty (of which climate sensitivity is an example), model uncertainty (the structure of the damage function is a noted example), normative uncertainly (the discount rate is a notorious example), the uncertainty of rates of change of exogenous variables (e.g. of population, total factor productivity, and carbon and energy intensity) and others. See Cai (2020) and Gillingham et al. (2018) for review and discussion of uncertainty. Small differences in the values and functional forms chosen for many of these variables can generate enormous differences in outcomes, yet many of these variables are inherently highly uncertain. Many are highly abstracted conceptual entities created to fit within a mathematical framework initially devised to model the behavior of cannonballs and steam engines. See Pindyck (2017) for critical comment.

REFERENCES

Andrews, Roger. 2018. “Why ‘demand response’ won’t work.” *Energy Matters.* http://euanmearns.com/why-demand-response-wont-work/ . 17 May.

Athanasiou, Tom. 2020. “It’s Time for the US to Carry Its Fair Share on Climate Change.” *Sierra Magazine.* 2 December.

Baer, Paul, and John Harte, Barbara Haya, Antonia V. Herzog, John Holdren, Nathan E. Hultman, Daniel M. Kammen, Richard B. Norgaard and Leigh Raymond. 2000. “Equity and Greenhouse Gas Responsibility.” *Science,* Vol. 289, Issue 5488, pp. 2287. 29 September. https://science.sciencemag.org/content/289/5488/2287.full

Balasubramanian, Govindasamy, Phillip Duffy and K.E. Taylor. 2008. “Impact of geoengineering schemes on the global hydrological cycle.” *PNAS.* 03 June.

Basten, Stuart, Wolfgang Lutz and Sergei Scherbov. 2013. “Very long range global population scenarios to 2300 and the implications of sustained low fertility.” *DEMOGRAPHIC RESEARCH.* 30 May. http://www.demographic-research.org/Volumes/Vol28/39/ DOI: 10.4054/DemRes.2013.28.39 Reflection

Blagoeva, D.T., P. Alves Dias, A. Marmier, and C.C. Pavel. 2016. “Assessment of potential bottlenecks along the materials supply chain for the future deployment of low-carbon energy and transport technologies in the EU. Wind power, photovoltaic and electric vehicles technologies, time frame: 2015-2030.” European Commission. EUR 28192 EN; doi:10.2790/08169

Boucher, O., D. Randall, P. Artaxo, C. Bretherton, G. Feingold, P. Forster, V.-M. Kerminen, Y. Kondo, H. Liao, U. Lohmann, P. Rasch, S.K. Satheesh, S. Sherwood, B. Stevens and X.Y. Zhang. 2013. Clouds and Aerosols. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Bundesanstalt für Geowissenschaften und Rohstoffe (BGR). 2019. Energy Study 2018: Data and Developments Concerning German and Global Energy Supplies. August. Hannover.

Burke, Jan, and Ursala Hagen, Franziska Marten, Niklas Hoehne, Christoph Bals. 2018. *Climate Change Performance Index: Results 2019.* December. Bonn: Germanwatch.org.

BP. 2019. *BP Statistical Review of World Energy – 68th edition*. London: United Kingdom.

Bricker, Darrell and John Ibbitson. 2019. *Empty Planet: The Shock of Global Population Decline*. Oxford U.K.: Signal.

Brovkin, Victor and Vladimir Petoukhov, Martin Claussen, Eva Bauer, David Archer and Carlo Jaeger. 2008. “Geoengineering climate by stratospheric sulfur injections: Earth system vulnerability to technological failure.” *Climate Change, 92.* 17 September.

Cai, Yongyang. 2020. *The Role of Uncertainty in Controlling Climate Change.* Department of Agriculture, Environmental and Development Economics, The Ohio State University. 4 March.

Cai, Yongyang, Timothy M. Lenton and Thomas S. Lontzek. 2016. “Risk of multiple interacting tipping points should encourage rapid CO_2 emission reduction”. *Nature Climate Change* 6**,** 520–525. https://doi.org/10.1038/nclimate2964

Carbon Brief. 2018. *The Impacts of Climate Change at 1.5C, 2.0C and Beyond*. 4 October.

Carvallo, Juan Pablo. 2020. Consultation.

Charney, Jule G. 1979. *Carbon Dioxide and Climate: A Scientific Assessment. Report of an Ad Hoc Study Group on Carbon Dioxide and Climate.* Washington D.C.: National Academy of Sciences.

Cho, Adrian. 2010. Energy's tricky tradeoffs. *Science*. 329:786–7.

Climate Advisors. 2018. *Creating Negative Emissions: The Role of Natural and Technological Carbon Dioxide Removal Strategies*. June.

Cline, William. 1992. *The Economics of Global Warming*. Institute for International Economics. Washington D.C.

Cohen, Rachel M. 2019. "The Environmental Left is Softening on Carbon-Capture Technology. Maybe that's OK." *The Intercept.* 20 September.

Cole, Wesley and A. Will Frazier. 2019. *Cost Projections for Utility-Scale Battery Storage.* National Renewable Energy Laboratory Technical Report. NREL/TP-6A20-73222. June.

Coleman, David and Robert Rowthorn. 2015. "Population Decline – Making the Best of Inevitable Destiny?" *History and Mathematics: Democracy and Aging.* Uchitel Publishing House: Volgograd.

Consoli, Christopher. 2019. Bioenergy and Carbon Capture and Storage. *Global CCS Institute*.

DeCicco John M. and William H. Schlesinger. 2018. "Opinion: Reconsidering bioenergy given the urgency of climate protection." *Proceedings of the National Academy of Sciences*. DOI: 10.1073/pnas.1814120115.

den Elzen, Michel G. J. and Detlef P. van Vuuven. 2007. "Peaking profiles for achieving long-term temperature targets with more likelihood at lower costs." PNAS, Vol 104 No. 46. 13 November.

Deng, Yvonne Y., Haigh M., Pouwels W., Ramaekers L., Brandsma R., Schimschar S., et al. 2015. "Quantifying a realistic, worldwide wind and solar electricity supply." Global Environmental Change. 31:239–52.

Denholm, Paul, Hand, M., Jackson, M., Ong, S. 2009. Land Use Requirements of Modern Wind Power Plants in the United States. National Renewable Energy Laboratory. August. (No. NREL/TP-6A2-45834, 964608). uraniumhttps://doi.org/10.2172/964608. https://doi.org/10.2172/964608

de Vries, Bert JM, van Vuuren DP, Hoogwijk MM. 2007. "Renewable energy sources: Their global potential for the first-half of the 21st century at a global level: An integrated approach." *Energy Policy* Vol 35, Issue 4. April.

Dunne, Daisy. 2018. "Explainer: Six ideas to limit global warming with solar geoengineering." *Carbon Brief.* 9 May.

European Academies Science Advisory Council (EASAC). 2018. Negative emission technologies: What role in meeting Paris Agreement targets? February.

Fajardy, Mathilde, Alexandre Koeberle, Niall MacDowell and Andrea Fantuzzi. 2019. BECCS deployment: A reality check. Grantham Institute Briefing paper No 28. Imperial College London. January.

Fajardy, Mathilde and Niall MacDowell. 2017. "Can BECSS deliver sustainable and resource efficient negative emissions?" *Energy & Environmental Science.* Vol 10, 1389.

Firestone, Jeremy and Willett Kempton. 2007. "Public opinion about large off share wind power: Underlying factors." Energy Policy. Vol 35, Issue 3. 26 January. doi: 10.1016/j.heliyon.2019.e01166

Folger, Peter. 2019. Carbon Capture and Sequestration (CCS) in the United States. CRS Report. Washington, D.C.: Congressional Research Service. 9 August.

Freeman, Christopher, and Marie Jahoda. 1978. *World Futures: The Great Debate*. New York: Universe Books.

Fricko, Oliver, and Petr Havlik, Joeri Rogelj, Zbigniew Klimont, Mykola Gustia, Nils Johnson, Peter Kolpa, Manfred Strubegger, HugoValin, Markus Amann, Tatiana Ermolieva, Nicklas Forsell, Mario Herrero, Chris Heyes, Georg Kindermann, Volker Krey, David L.McCollum, Michael Obersteiner, Shonali Pachauri, Shipa Rao, Erwin Schmid, Wolfgang Schoepp, and Keywan Riahi. 2017. The marker quantification of the Shared Socioeconomic Pathway 2: A middle-of-the-road scenario for the 21st century. *Global Environmental Change*. Volume 42, January. p251-267.

Frölicher, Thomas Lukas and Michael Winton and Jorge Louis Sarmiento. 2013. "Continued global warming after CO_2 emissions stoppage". *Nature Climate Change*. 24 November.

Frost, Matt. 2019. "After Climate Despair." *The New Atlantis*. Number 60, Fall, pp. 3-21.

Fuss, Sabine, and William F Lamb, Max W Callaghan, Jerome Hilaire, Felix Creutzig, Thorben Amann, Tim Beringer, Wagner de Oliveira Garcia, Jens Hartmann, Tarun Khanna, Gunnar Luderer, Gregory F Nemet, Joeri Rogelj, Pete, Jose Luis Vicente, Jennifer Wilcox, Maria del Mar Zamora Dominguez and Jan C Minx. 2018. "Negative emissions—Part 2: Costs, potentials and side effects". *Environmental Research Letters.* 13. 063002. 22 May.

Fuss, Sabine, C D Jones, F Kraxner, G P Peters, P Smith, M Tavoni, D P van Vuuren, J G Canadell, R B Jackson, J Milne, J R Moreira, N Nakicenovic, A Sharifi and Y Yamagara. 2016. "Research Priorities for Negative Emissions". *Environmental Research Letters*. 11. 115007. 17 November.

Fuss, Sabine et al. 2014. "Betting on Negative Emissions." *Nature Climate Change*. **4**, 850–853. 21 September.

Gambhir, Ajay, and Isabela Butnar, Pei-Hao Li, Pete Smith and Neil Strachan. 2019. A Review of Criticisms of Integrated Assessment Models and Proposed Approaches to Address These, through the Lens of BECCS. *Energies.* 8 May. www.mdpi.com/journal/energies.

Gauthier, Philippe. 2018. "The Limits of Renewable Energy and the Case for Degrowth." *Resistance.* 21 November. Originally published in *Canadian Dimension.*

Gertner, Jon. 2020. "The Carbon Chase." *New York Times Magazine*. 12 February.

Gillingham, Kenneth, and William Nordhaus, David Anthoff, Geoffrey Blanford, Valentina Bosetti, Peter Christensen, Haewon McJeon, and John Reilly. 2018. "Modeling Uncertainty in Integrated Assessment of Climate Change: A Multi-Model Comparison." *Journal of the Association of Environmental and Resource Economists.* Vol. 5, No. 4, October.

Goes, Marlos and Nancy Tuana and Klaus Keller. 2011. "The economics (or lack thereof) of aerosol geoengineering." *Climate Change*. 5 April.

Goldstein, B.A., Hiriart, G., Tester, J. B., Bertani, R., Bromley, Gutierrez-Negrin, L., C. J., Huenges, E. H., Ragnarsson, A., Mongillo, M.A. Muraoka, and V. I. Zui. 2011. "Great Expectations in Geothermal Energy to 2100." *PROCEEDINGS,* Thirty-Sixth Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA. 31 Jan – 2 Feb. SGP-TR-191.

Gough, Clair and Samira Garcia-Freites, Christopher Jones, Sarah Mander, Brendan Moore, Cristina Pereira, Mirjam Roeder, Naomi Vaughn and Welfle, Andrew. 2018. "Challenges to the use of BECCS as a keystone technology in pursuit of 1.5°C". *Global Sustainability, 1*, E5. doi:10.1017/sus.2018.3.

GreenPeace Southeast Asia. 2020. *Southeast Asia Power Sector Scorecard: Assessing the progress of national energy transitions against a 1.5 degrees pathway*. September.

Grieger, Khara D., Tyler Felgenhauer, Ortwin Renn, Jonathan Wiener and Mark Borsuk. 2019. "Emerging risk governance for stratospheric aerosol injection as a climate management technology." *Environment Systems and Decisions.* 30 April. https://research.ncsu.edu/ges/files/2019/05/Grieger2019_Article_EmergingRiskGovernanceForStrat.pdf

Griffith, Saul, with Laura Fraser and Sam Calisch. 2020. *REWIRING AMERICA: A Field Manual for the Climate Fight.* Rewiring America*.* 29 July.

Griffith, Saul, and Sam Calisch and Alex Laskey. 2020. *Mobilizing for a zero carbon America: A Jobs and Employment Study Report.* Rewiring America. 29 July.

Gross, Robert, Leach M., Bauen A. 2003. "Progress in renewable energy". *Environment International*; 29:105–22.

Hafele, Wolfgang. 1981. *Energy in a finite world: a global systems analysis*. Cambridge, MA: Ballinger.

Hanna, Ryan, Ahmed Abdulla, Yangyang Xu, David G. Victor. 2021. "Emergency deployment of direct air capture as a response to the climate crisis." *Nature Communications*. 12:368. doi.org/10.1038/s41467-020-20437-0.

Harper, Anne. 2018. Why BECCS might not produce negative emissions after all. *CarbonBrief.com.* 14 August.

Harris, Gardiner. 2014. "Borrowed Time on Disappearing Land. *New York Times.* 28 March.

Hausfather, Zeke. 2018. Explainer: How Scientists Estimate Climate Sensitivity. *CarbonBrief.org*. 19 June.

Hendriks, Chris, Wina Graus and Frank van Bergen. 2004. Global carbon dioxide storage potential and costs. *Ecofys/TNO-NITG* . Utrecht: Rijksinstituut voor Volksgezondheid en Milieu.

Holdren, John P. 1995. "Recent World Energy and Economic Data." Energy and Resources 200 course handout. University of California at Berkeley. October.

Houghton, J.T., Filho, L.G.M., Callander, B.A., Harris, N., Kattenburg, A., Maskell, K. (Eds.), 1996. Climate Change 1995: The Science of Climate Change: Contribution of Working Group I to the Second Assessment Report of the Intergovernmental Panel on Climate Change, 1996 edition. Cambridge University Press: New York.

House, Kurt Zena, Antonio C Baclig, Manya Ranjan, Ernst A van Nierop, Jennifer Wilcox and Howard J Herzog. 2011. "Economic and energetic analysis of capturing CO2 from ambient air." *Proc Natl Acad Sci USA*. 20 December. 108(51):20428-33. doi: 10.1073/pnas.1012253108.

Hu, Yuanan & Cheng, Hefa. 2013. "Development and Bottlenecks of Renewable Electricity Generation in China: A Critical Review." *Environmental Science & Technology*. 47. 10.1021/es303146q.

Huntingford, Chris and Jason Lowe. 2007. "'Overshoot' Scenarios and Climate Change." *Science* Vol 316. 11 May.

IEAGHG. 2011. "Potential for Biomass and Carbon Dioxide Capture and Storage". *International Energy Agency Greenhouse Gas Research & Development Programme*. Paris.

International Atomic Energy Agency (IAEA) and OCED Nuclear Energy Agency (NEQ). 2006. *Uranium 2005: Resources, Production and Demand.* https://www.iaea.org/newscenter/news/global-uranium-resources-meet-projected-demand. 2 June.

Intergovernmental Panel on Climate Change (IPCC). 2018. *Global Warming of 1.5°C. An IPCC Special Report.* Chapter 3: “Impacts of 1.5°C of Global Warming on Natural and Human Systems.” Contributing lead authors: Ove Hoegh-Guldberg, Daniela Jacob and Michael Taylor. Cross-Chapter Box 7, Table 1, p.270.

Intergovernmental Panel on Climate Change (IPCC). 2014: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)]. Cambridge University Press: Cambridge, United Kingdom and New York, NY, USA.

Intergovernmental Panel on Climate Change (IPCC). 2013. “Summary for Policymakers”. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press: Cambridge, United Kingdom and New York, NY, USA.

Intergovernmental Panel on Climate Change (IPCC). 2013. *AR5 Technical Summary.* Stocker, T.F., D. Qin, G.-K. Plattner, L.V. Alexander, S.K. Allen, N.L. Bindoff, F.-M. Bréon, J.A. Church, U. Cubasch, S. Emori, P. Forster, P. Friedlingstein, N. Gillett, J.M. Gregory, D.L. Hartmann, E. Jansen, B. Kirtman, R. Knutti, K. Krishna Kumar, P. Lemke, J. Marotzke, V. Masson-Delmotte, G.A. Meehl, I.I. Mokhov, S. Piao, V. Ramaswamy, D. Randall, M. Rhein, M. Rojas, C. Sabine, D. Shindell, L.D. Talley, D.G. Vaughan and S.-P. Xie. Cambridge University Press: Cambridge, UK.
Intergovernmental Panel on Climate Change (IPCC). 2007. *AR4 Climate Change 2007: The Physical Science Basis.* Cambridge University Press: Cambridge, United Kingdom and New York, NY, USA.

Intergovernmental Panel on Climate Change (IPCC). 1996. *Climate Change 1995: Impacts, Adaptations and Mitigation of Climate Change;* Scientific-Technical Analysis. New York: Cambridge University Press.

International Institute for Applied Systems Analysis (IIASA). 2018. Shared Socio-Economic Pathways Database, Version 2.0. December.

International Institute for Applied Systems Analysis (IIASA). 2014. AMPERE Project. https://tntcat.iiasa.ac.at/AMPEREDB/dsd?Action=htmlpage&page=about

International Institute for Applied Systems Analysis (IIASA). 2012. Global Energy Assessment – Toward a Sustainable Future. New York: Cambridge University Press.

International Institute for Applied Systems Analysis/World Energy Council. 1995. “Global Energy Perspectives to 2050 and Beyond.” Laxemburg, Austria.

Iyer Gokul, Nathan Hultman, Jiyong Eom, Haewon McJeon, Pralit Patel, and Leon Clarke. 2013. “Diffusion of low-carbon technologies and the feasibility of long-term climate targets.” *Technological Forecasting and Social Change.* 27 September. ISSN 0040-1625, http://dx.doi.org/10.1016/j.techfore.2013.08.025.

Jenkins, Jesse D. and Armond M. Cohen. 2015. “The Role of Energy Intensity in Global Decarbonization: How Fast Can We Cut Energy Use?” Report of the Clean Air Task Force. 17 March.

Kahn, Herman, William Brown and Leon Martel. 1976. *The Next 200 Years*: *A Scenario for America and the World.* New York: William Morrow and Company.

Keith, David W., Debra K. Weisenstein, John A. Dykema, and Frank N. Keutsch. 2016. “Stratospheric solar geoengineering without ozone loss.” *PNAS* vol 113, no. 52. 27 December.

Keith, David W., and Douglas G. MacMartin. 2015. “A temporary, moderate and responsive scenario for solar geoengineering.” *Nature Climate Change.* 16 February.

Keith, David. 2013. *A Case for Climate Engineering.* New York: Boston Review.

Kelemen, Peter. 2020. Columbia University. Cited in Kramer (2020).

Kittner, Noah and Felix Lilla and Daniel M. Kammen. 2017. “Energy storage deployment and innovation for the clean energy transition.” *Nature Energy,* Vol 2, Article 17125. 31 July.

Klimenko Vladimir, Tereshin AG, Mikushina OV. 2009. “Global energy and climate of the planet in the XXI century in the context of historical trends.” *Russian Journal of General Chemistry*. 79(11):2469–76.

Kramer, David. 2020. “Negative carbon dioxide emissions.” *Physics Today,* 73. January.

Kramer, Gert Jan and Martin Haigh. 2009. “No quick switch to low-carbon energy.” *Nature,* Volume 462, Issue 7273, pp. 568-569. 3 December.

Kriegler, Elmar, Jim W. Hall, Hermann Held, Richard Dawson, and Hans Joachim Schellnhuber. 2009. “Imprecise probability assessment of tipping points in the climate system.” Proceedings of the National Academy of Sciences 106 (13):5041–5046.

Kropowski, Benjamin. 2018. *Integrating high levels of variable renewable energy into electric power systems.* National Renewable Energy Laboratory (NREL). December.

Lauvset, Siv K., Jerry Tjiputra and Helene Muri. 2017. “Climate engineering and the ocean: effects on biogeochemistry and primary production.” *Biosciences,* 14. 20 December.

Larsen, Edward J. 2016. “The Red Dawn of Geoengineering: First Steps Toward an Effective Governance for Stratospheric Injections.” *Duke Law Review,* Vol. 14 No. 1.

Lawrence, Mark G. and Stefan Schaefer, Helene Muri, Vivian Schott, Andreas Oschlies, Naomi Vaughan, Olivier Boucher, Hauke Schmidt, Jim Haywood and Jurgen Scheffran. 2018. “Evaluating climate geoengineering proposals in the context of the Paris Agreement temperature goals.” *Nature Communications.* DOI 10.1038/s41467-018-05938-3.

Leber, Rebecca. 2019. “Climate Change Is Finally Having a Political Moment. That’s No Accident.” *Mother Jones.* 2 December.

Lenton, Timothy M., Johan Rockström, Owen Gaffney, Stefan Rahmstorf, Katherine Richardson, Will Steffen & Hans Joachim Schellnhuber. 2019. “Climate tipping points — too risky to bet against.” *Nature*, 27 November. https://www.nature.com/articles/d41586-019-03595-0 .

Lenton, Timothy M. 2010. The potential for land-based biological CO_2 removal to lower future atmospheric CO_2 concentration. *Carbon Management.* 10 April.

Lenton, Timothy M. 2014. CHAPTER 3. The Global Potential for Carbon Dioxide Removal. *Geoengineering of the Climate System*. Cambridge: The Royal Society of Chemistry.

Levy, Gabriel. 2020. “Carbon dioxide removal sucks.” *The Ecologist.* 13 November.

Lightfoot, HD, and C. Green. 2002. "An assessment of IPCC Working Group 111 findings." In *Climate Change* 2001: Mitigation of the potential contribution of renewable energies to atmospheric carbon dioxide stabilization. Centre for Climate and Global Change Research (C2GCR) C2GCR Report No. 2002–5.

Loftus, Peter, Armond Cohen, Jane Long, and Jesse Jenkins. 2015. "A critical review of global decarbonization scenarios: what do they tell us about feasibility?" *Climate Change.* 6: 93-112.

Lowe, J.A., and C Huntingford, SCB Raper, CD Jones, SK Liddicoat and LK Gohar. 2009. "How difficult is it to recover from dangerous levels of global warming?" *Environmental Research Letters* 4 (January-March) 014012 doi:10.1088/1748-9326/4/1/014012.

Lutz, Wolfgang, and Warren C. Sanderson, Sergei Scherbov, eds. 2013 (first published 2004). *The End of Population Growth in the 21st Century. New Challenges for Human Capital Formation and Sustainable Development.* London: Routledge.

Ma, Ookie et al. 2013. "Demand Response for Ancillary Services". *IEEE Transaction on Smart Grid*, Vol 4 Issue 4. December.

MacMartin, Douglas G., Katharine L. Ricke and David W. Keith. 2018. "Solar geoengineering as part of an overall strategy for meeting the 1.5°C Paris target." *The Philosophy Society.* 2 April.

Manley, David and Patrick R.P. Heller. 2021. *Risky Bet: National Oil Companies in the Energy Transition.* New York*:* National Resource Governance Institute. February.

Matthews, H. Damon and Ken Caldeira. 2008. "Stabilizing climate requires near-zero emissions." *Geophysical Research letters,* Vol 35. 27 February.

Matthews, H. Damon and Ken Caldeira. 2007. "Transient climate-carbon simulations of planetary geoengineering." *PNAS.* 12 June. https://www.pnas.org/content/pnas/104/24/9949.full.pdf

McGlashan Niall, Shah N, Caldecott B and Workman M. 2012. "High-level techno-economic assessment of negative emissions technologies." *Process Safety and Environmental Protection.* 90. November.

McKibben, Bill. 2020. "Citing Climate Change, BlackRock Will Start Moving Away from Fossil Fuels." *The New Yorker.* 16 January.

McQueen, Noah, and Peter Psarras, Hélène Pilorgé, Simona Liguori, Jiajun He, Mengyao Yuan, Caleb M. Woodall, Kourosh Kian, Lara Pierpoint, Jacob Jurewicz, J. Matthew Lucas, Rory Jacobson, Noah Deich, and Jennifer Wilcox. 2020. "Cost Analysis of Direct Air Capture and Sequestration Coupled to Low-Carbon Thermal Energy in the United States." *Environmental Science and Technology*. 54, 12, 7542–7551. 15 May. https://doi.org/10.1021/acs.est.0c00476

Meinshausen, M., Nicholls, Z. R. J., Lewis, J., Gidden, M. J., Vogel, E., Freund, M., Beyerle, U., Gessner, C., Nauels, A., Bauer, N., Canadell, J. G., Daniel, J. S., John, A., Krummel, P. B., Luderer, G., Meinshausen, N., Montzka, S. A., Rayner, P. J., Reimann, S., Smith, S. J., van den Berg, M., Velders, G. J. M., Vollmer, M. K., and Wang, R. H. J. 2020. "The shared socio-economic pathway (SSP) greenhouse gas concentrations and their extensions to 2500." *Geoscience Model Development, 13*, 3571–3605, https://doi.org/10.5194/gmd-13-3571-2020 13 August.

Meinshausen, Malte & S. J. Smith & K. Calvin & J. S. Daniel & M. L. T. Kainuma & J-F. Lamarque & K. Matsumoto & S. A. Montzka & S. C. B. Raper & K. Riahi & A. Thomson & G. J. M. Velders & D.P. P. van Vuuren. 2011. "The RCP greenhouse gas concentrations and their extensions from 1765 to 2300." *Climate Change.* 109:213–241.

Minx, Jan C., Max W. Callaghan, Jae Edmonds, Gunnar Luderer, Gregory F. Nemet, Joeri Rogelj and Maria del Mar Zamora. 2019. “Negative emissions and international climate goals—learning from and about mitigation scenarios.” *Climate Change.* 157. 17 October.

Minx, Jan C., William F Lamb, Max W Callaghan, Sabine Fuss, Jérôme Hilaire, Felix Creutzig, Thorben Amann, Tim Beringer, Wagner de Oliveira Garcia, and Jens Hartmann. 2018. “Negative emissions – Part 1: Research landscape and synthesis”. *Environmental Research Letters*. 13. 22 May.

Mishra, Anik. 2018. “How to get India’s clean energy and EV push (back) on track.” *EnergyPost.eu.* 22 March.

Moriarty, Patrick and Damon Honnery. 2012.What is the global potential for renewable energy? *Renewable and Sustainable Energy Reviews.* Vol 16 Issue 1. January.

Morice, C.P., J.J. Kennedy, N.A. Rayner, J.P. Winn, E. Hogan, R.E. Killick, R.J.H. Dunn, T.J. Osborn, P.D. Jones and I.R. Simpson. 2020. “An updated assessment of near-surface temperature change from 1850: the HadCRUT5 dataset.” *Journal of Geophysical Research (Atmospheres)* doi:10.1029/2019JD032361. 15 December.

Muri, Helen. 2018. The role of large-scale BECCS in the pursuit of the 1.5 degree C target: an earth system model perspective. *Environmental Research Letters.* Vol 13. 26 March.

Nachmany, Machal and Emily Mangan. 2018. *Aligning national and international climate targets.* London: Grantham Research Institute on Climate Change and the Environment. October.

National Academy of Sciences, Engineering and Medicine. 2019. *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda.* Washington, D.C.: National Academies Press.

National Academies of Science. 2009. America’s Energy Future: Technology and Transformation. Washington D.C. National Academies Press. https://doi.org/10.17226/12091.

National Research Council. 2015. *Climate Intervention: Carbon Dioxide Removal and Reliable Sequestration*. Washington D.C.: National Academies Press.

New York State Department of Environmental Conservation. 2020. “DEC Announces Finalization of 'Value of Carbon' Guidance to Help Measure Impacts of Greenhouse Gas Emissions.” New York State DEC. 30 December.

Nijsse, F. J. M. M., Cox, P. M., and Williamson, M. S. 2020. “Emergent constraints on transient climate response (TCR) and equilibrium climate sensitivity (ECS) from historical warming in CMIP5 and CMIP6 models.” *Earth System Dynamics,* 11, 737–750,

Nordhaus, William and Paul Sztorc. 2013. *DICE 2013R: Introduction and User’s Manual.* October. Yale Department of Economics.

Nordhaus, William. 2010. *RICE2010.beta.4.012510.* https://sites.google.com/site/williamdnordhaus/dice-rice [The RICE model used in this exercise was formerly available at this URL but appears to have been removed at some point prior to Feb. 2020.]

Ogden, Joan M. and Robert H. Williams. 1989. *Solar Hydrogen: Moving Beyond Fossil Fuels*. Washington, DC: World Resources Institute.

O’Neill, Brian C., and Elmar Krieger, Keywan Riahi, Kristie L. Ebi, Stephane Hallegatte, Timothy R. Carter, Ritu Mathur and Detlef P. van Vuuren. 2014. “A new scenario framework for climate change research: the concept of shared socioeconomic pathways.” *Climate Change* 122: 387-400.

Osaka, Shannon. 2020. "The Paris Agreement set an unrealistic target for global warming. Now what?" *Grist.com.* 12 February.

Ong, Sean, Campbell, C., Denholm, P., Margolis, R., Heath, G. 2013. Land-Use Requirements for Solar Power Plants in the United States. National Renewable Energy Laboratory. June. (No. NREL/TP-6A20-56290, 1086349). https://doi.org/10.2172/1086349

Otto, Ilona M. and Jonathan F. Donges, Roger Cremades, Avit Bhowmik, Richard J. Hewitt, Wolfgang Lucht, Johan Rockström, Franziska Allerberger, Mark McCaffrey, Sylvanus S. P. Doe, Alex Lenferna, Nerea Morán, Detlef P. van Vuuren, and Hans Joachim Schellnhuber. 2020. "Social tipping dynamics for stabilizing Earth's climate by 2050." PNAS. 117 (5) 2354-2365. 4 February.

Parker, Andy, & Irvine, P. J. 2018."The Risk of Termination Shock From Solar Geoengineering." *Earth's Future,* 6, 456-467. https://doi.org/10.1002/2017EF000735. 11 March.

Perkins, Sid. 2011. "Earth Still Retains Much of its Original Heat." *Science.* 17 July.

Peters, Glen P. and Oliver Geden. 2017. "Catalyzing a political shift from low to negative carbon." *Nature Climate Change,* Vol 7. September.

Pindyck, Robert S. 2015. The Use and Misuse of Models for Climate Policy. NBER Working Paper No. 21097. April.

Piper, Kelsey. 2019. "Is climate change an 'existential threat' - or just a catastrophic one?" *Vox.com*. 28 June.

Realmonte, Giulia, Laurent Drouet, Ajay Gambher, James Glynn, Adam Hawkes, Alexandre Koeberle and Massimo Tavoni*.* 2019. "An inter-model assessment of the role of direct air capture in deep mitigation pathways." *Nature Communications* 10**,** 3277. https://doi.org/10.1038/s41467-019-10842-5.

Reid, Walter V. and Mariam K. Ali and Christopher B. Field. 2019. *The Future of Bioenergy, Global Change Biology*. Vol 26 Issue 1. DOI: 10.1111/gcb.14883

Reilly, John and Sergey Paltsev. 2008. Biomass Energy and Competition for Land. Joint Program on the Science and Policy of Global Change. MIT: Cambridge, MA.

Resch, Gustav, Held A, Faber T, Panzer C, Toro F, Haas R. 2008. Potentials and prospects for renewable energies at global scale. *Energy Policy*. 36:4048–56.

Reynolds, Jesse L. 2020. "Is solar geoengineering ungovernable? A critical assessment of governance challenges identified by the Intergovernmental Panel on Climate Change." *WIREs Climate Change*. 11 November.

Reynolds, Jesse L. 2019a. "Solar Geoengineering to Reduce Climate Change: A Review of Governance Proposals." *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences* 475 (2229): article 20190255. https://doi.org/10.1098/rspa.2019.0255.

Reynolds, Jesse L. 2019b. *The Governance of Solar Geoengineering: Managing Climate Change in the Anthropocene.* Cambridge, UK*:* Cambridge University Press.

Riahi, Keywan, and D. P. van Vuuren, E. Kriegler, J. Edmonds, B. C. O'Neill, S. Fujimori, N. Bauer, K. Calvin, R. Dellink, O. Fricko, W. Lutz, A. Popp, J. C. Cuaresma, Samir KC, M. Leimbach, L. Jiang, T. Kram, S. Rao, J. Emmerling, K. Ebi, T. Hasegawa, P. Havlik, F. Humpenöder, L. Aleluia Da Silva, S. Smith, E. Stehfest, V. Bosetti, J. Eom, D. Gernaat, T. Masui, J. Rogelj, J. Strefler, L. Drouet, V. Krey, G. Luderer, M. Harmsen, K. Takahashi, L. Baumstark, J. C. Doelman, M. Kainuma, Z. Klimont, G. Marangoni, H. Lotze-Campen, M. Obersteiner, A. Tabeau, M. Tavoni. 2017. "The

Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview." *Global Environmental Change.* Volume 42, January. Pages 153-168.

Roberts, David. 2020. Social Tipping Points are the Only Hope for the Climate. *Vox.com*. 29 January.

Robock, Alan. 2014. "Stratospheric Aerosol Geoengineering." *Issues in Environmental Science and Technology,* 38.

Robock, Alan. 2009. "The Many Problems with Geoengineering Using Stratospheric Aerosols." Presentation at the American Physical Society Meeting in Denver. May.

Rogelj, Joeri and William Hare, Jason Lowe, Detlef P. van Vuuren, Keywan Riahi, Ben Matthews, Tatsuya Hanaoka, Kejun Jiang and Malte Meinshausen. 2011. "Emission pathways consistent with a 2.0˚C global temperature limit." *Nature Climate Change.* Letters. 23 October.

Sachs, Noah. 2019. The Paris Agreement in the 2020s: Breakdown or Breakup? *Ecology Law Quarterly,* Vol. 46, No. 1. 3 October. Available at SSRN: https://ssrn.com/abstract=3463892

Saeed, Fahad, Cari-Friedrich Schleussner, and William Hare. 2018. "Why geoengineering is not a solution to the climate problem." *Climate Analysis.* 12 February.

Sanchez, Daniel. University of California, Berkeley. Quoted in Kramer, David (2020).

Schmidt, Gavin. 2020. "Climate Sensitivity: A New Assessment." *RealClimate.org*. 22 July.

Seetharaman, Krishna Moorthy, Nitin Patwa, Saravanan, and Yash Guptaa. 2019. "Breaking barriers in deployment of renewable energy" . *Heliyon*. 26 January. 5(1): doi: 10.1016/j.heliyon.2019.e01166

Sekera, June and Andreas Lichtenberger. 2020. "Assessing Carbon Capture: Public Policy, Science, and Societal Need A Review of the Literature on Industrial Carbon Removal." *Biophysical Economics and Sustainability* 5:14. 19 June. https://doi.org/10.1007/s41247-020-00080-5

Sherwood, S.C and M.J. Webb, J.D. Annan, K.C. Armour, P.M. Forster, J.C. Hargreaves, G. Hegerl, S.A. Klein, K.D. Marvel, E.J. Rohling, M. Watanabe, T. Andrews, P. Braconnot, C.S. Bretherton, G.L. Foster, Z. Hausfather, A.S. von der Heydt, R. Knutti, T. Mauritsen, J. R. Norris, C. Proistosescu, M. Rugenstein, G. A. Schmidt, K. B. Tokarska, and M.D. Zelinka. 2020. "An Assessment of Earth's Climate Sensitivity Using Multiple Lines of Evidence." *Reviews of Geophysics.* 22 July.

Siegel, R.F. 2019. "Building the Ultimate Carbon Capture Tree." *American Society of Mechanical Engineers.* 17 May.

Sims, REH, Schock RN, Adegbululgbe A, Fenhann J, Konstantinaviciute I, Moomaw W, et al. *Energy Supply.* In: Metz B, Davidson OR, Bosch PR, Dave R, Meyer LA, editors. *Climate Change 2007: Mitigation.* Cambridge, UK: CUP.

Smalley, Richard E. 2005. "Future Global Energy Prosperity: The Terawatt Challenge". *Complex Adaptive Matter: Emergent Phenomena in Materials. Vol 30, Issue 6. June.*

Smil, Vaclav. 2003. *Energy at the Crossroads: global perspectives and uncertainties*. Cambridge MA: MIT Press.

Smith, Pete, Davis, S.J., Creutzig, F., Fuss, S., Minx, J., Gabrielle, B., Kato, E., Jackson, R.B., Cowie, A., Kriegler, E., van Vuuren, D.P., Rogelj, J., Ciais, P., Milne, J., Canadell, J.G., McCollum, D., Peters, G., Andrew, R., Krey, V., Shrestha, G., Friedlingstein, P., Gasser, T., Grübler, A., Heidug, W.K., Jonas, M., Jones, C.D., Kraxner, F., Littleton, E., Lowe, J., Moreira, J.R., Nakicenovic, N., Obersteiner, M., Patwardhan, A., Rogner, M., Rubin, E., Sharifi, A., Torvanger, A., Yamagata, Y., Edmonds, J., Yongsung, C. 2015. Biophysical and economic limits to negative CO2 emissions. *Nature Climate Change* 6. 42–50.

Smith, Steven J. and Philip J. Rasch. 2012. "The long-term policy context for solar radiation management." *Climate Change.* 6 October.

Smith, Wake. 2020. "The cost of stratospheric aerosol injection through 2100." *Environmental Research Letters.* In press. https://iopscience.iop.org/article/10.1088/1748-9326/aba7e7 .

Socolow Robert, et al. 2011. *Direct Air Capture of CO2 with Chemicals: A Technology Assessment for the APS Panel on Public Affairs.* American Physical Society. 1 June.

Solomon, Susan, Plattner, G.-K., Knutti, R., Friedlingstein, P. 2009. "Irreversible climate change due to carbon dioxide emissions." *PNAS* 106, 1704–1709. https://doi.org/10.1073/pnas.0812721106.

Spratt, David, Ian Dunlop and Luke Taylor. 2020. *Climate Reality Check 20: Impacts, Risks, Actions.* Breakthrough-National Centre for Climate Restoration. October.

Steffen, Will, J. Rockström, K. Richardson, T. M. Lenton, C. Folke, D. Liverman, C. P. Summerhayes, A. D. Barnosky, S. E. Cornell, M. Crucifix, J. F. Donges, I. Fetzer, S. J. Lade, M. Scheffer, R. Winkelmann, and H. Joachim Schellnhuber. 2018. "Trajectories of the Earth System in the Anthropocene." PNAS, vol 115, no. 33. 14 August.

Stein Emil et al. 2020. "Fertility, mortality, migration, and population scenarios for 195 countries and territories from 2017 to 2100: a forecasting analysis for the Global Burden of Disease Study". *The Lancet*. 17 October. DOI: 10.1016/S0140-6736(20)30677-2

Stern, Nicholas and Joseph E. Stiglitz. 2021. Getting the Social Cost of Carbon Right. *Project Syndicate.* 15 February.
Svoboda, Toby, Peter J. Irvine, Daniel Callies, and Masahiro Sugiyama. 2019. "The Potential for Climate Engineering with Stratospheric Sulfate Aerosol Injections to Reduce Climate Injustice." *Journal of Global Ethics* 14 (3): 353–68.

Svoboda, Toby, Klaus Keller, Marlos Goes and Nancy Tuana. 2011. "Sulfate Aerosol Geoengineering: The Question of Justice." *Public Affairs Quarterly,* Vol. 25, No. 3. July.

Tjiputra, Jerry F., A. Grini and H. Lee. 2015. "Impact of idealized future stratospheric aerosol injection on the large-scale ocean and land carbon cycles." *Journal of Geological Research: Biosciences.* 14 December.

Tol, Richard and David Anthoff. 2019. Mini-FUND: https://github.com/fund-model/MimiFUND.jl

Tomabechi, Ken. 2010. Energy resources in the future. *Energies*. 3:686–95, doi:10.3390/en3040686.

United Nations. 2020. "Net-Zero Emissions Must Be Met by 2050 or COVID-19 Impact on Global Economies Will Pale Beside Climate Crisis, Secretary-General Tells Finance Summit." Statement by UN Secretary-General António Guterres. 12 November.

United Nations, Department of Economic and Social Affairs, Population Division. 2019. *World Population Prospects 2019,* Volume I: Comprehensive Tables (ST/ESA/SER.A/426).World Population Prospects 2019, Volume I: Comprehensive Tables (un.org)

United Nations Department of Economic and Social Affairs, Population Division. 2004. *World Population to 2300.* New York: United Nations.

United Nations Development Program (UNDP). 2000. World Energy Assessment: Energy and the Challenge of Sustainability. 2000. New York.

United Nations Environmental Programme (UNEP). 2020. *Emissions Gap Report 2020.* Nairobi.

United Nations Environmental Programme (UNEP) et al. 2020. *The Production Gap: 2020 Report*. Nairobi.

United States Energy Information Administration (USEIA). *Today in Energy 2019.* Washington D.C.

Vaughan, Adam. 2020. "Earth may be even closer to 1.5°C of global warming than we thought." *New Scientist.* 15 December.

Vaughn, Naomi F. and Timothy Lenton. 2011. "A Review of Climate Engineering Proposals." *Climate Change.* 22 March.

van Vuuren, Detlef P et al. 2016. "Carbon budgets and energy transition pathways". *Environmental Research Letters* 11 075002. 14 July.

van Vuuren, Detlef P and Sebastiaan Deetman, Jasper van Vliet, Maarten van den Berg, Bas J. van Ruijven & Barbara Koelbl. 2013. "The role of negative CO2 emissions for reaching 2°C—insights from integrated assessment modelling." *Climatic Change*, V 118 (15-27).

Walker, Robert. 2019. "Climate Change Will NOT End Human Civilization By 2050…" *Science 2.0.com*. 5 June.

Wallace-Wells, David. 2021. "After Alarmism: The war on climate denial has been won." *New York Magazine.* 21 January.

Walsh, B., Ciais, P., Janssens, I. et al. 2017. "Pathways for balancing CO_2 emissions and sinks". *Nature Commun*ications 8**,** 14856. https://doi.org/10.1038/ncomms14856m .

Watson, Sir Robert, and James. M. McCarthy, Pablo Canziani, Nebojsa Nakicenovic, Liliana Hisas. 2019. *The Truth Behind the Climate Pledges.* November. Washington D.C.: Fundacion Ecologica Universal FEU-US.

Wetter, Kathy Jo and Trudi Zundel. 2018. *The Big, Bad Fix: The Case Against Climate Geoengineering*. Quebec, Canada: The ETC Group.

Wigley, T.M.L. 2006. "A Combined Mitigation/Geoengineering Approach to Climate Stabilization." *ScienceExpress.* 14 September. http://www.essc.psu.edu/essc_web/seminars/fall2006/WigleySci06.pdf

Wigley, Tom & Richels, R.G. & Edmonds, J.A. 2007. Overshoot pathways to CO2 stabilization in a multi-gas context. *Human-Induced Climate Change: An Interdisciplinary Assessment.* 84-92. 10.1017/CBO9780511619472.009.

Williams, Jim H., Jones, R. A., Haley, B., Kwok, G., Hargreaves, J., Farbes, J., & Torn, M. S. 2021. *Carbon-neutral pathways for the United States.* AGU Advances, 2, e2020AV000284. https:// doi.org/10.1029/2020AV000284

World Energy Council (WEC). 2010. *2010 survey of energy resources*. London: World Energy Council.

Zelinka, Mark D., Timothy A. Myers, Daniel T. McCoy, Stephen Po-Chedley, Peter M. Caldwell, Paulo Ceppi, Stephen A. Klein, and Karl E. Taylor. 2020. "Causes of Higher Climate Sensitivity in CMIP6 Models." *Geophysical Research Letters.* 3 January.

# # #