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Greenhouse Gas Emissions Scenarios: Background, Issues, and Policy Relevance

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Greenhouse Gas Emissions Scenarios: Background, Issues, and Policy Relevance

SUMMARY

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June 3, 2021

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Projecting future climate change, and what drives it, is difficult, with many uncertainties. Computer models, however, can be useful tools for exploring the long-term implications of climate change and evaluating policy options. For example, models can help construct plausible scenarios of future greenhouse gas (GHG) emissions based on socioeconomic, environmental, and technological trends and drivers.

Integrated assessment models (IAMs), coupled models of the economy, energy, land use, and climate systems, are used by the Intergovernmental Panel on Climate Change (IPCC), the main international scientific body for assessing global climate change. This report explores the results of a selected set of IAM scenarios consistent with keeping the increase in global mean surface temperature to 1.5°C or 2°C above preindustrial levels in 2100, the temperature goal of the Paris Agreement. The modeling indicates that the more stringent the temperature target, the earlier the dates would have to be for global peak and net-zero carbon dioxide (CO_2) emissions. In order to hold *likely* (with at least a 66% probability) warming to below 2°C in 2100, the model results suggest that global annual CO_2 emissions would need to decline to net-zero between 2080 and 2100. To keep *likely* warming below 1.5°C in 2100, the models project that global CO_2 emissions would generally have peaked around 2020 and would reach net-zero by 2060. In these scenarios, carbon removal would need to balance positive GHG emissions. The IPCC scenarios indicate that the later the peak in CO_2 emissions, the sharper the reductions would be later in the century to hold the temperature increase below any given target.

With current technologies and projected future technology costs, the global IAM models in this report all generally rely on, inter alia, a scaling up of energy efficiency, renewable energy, nuclear energy, electrification of end-use energy, and large-scale deployment of negative emissions technologies to find lowest-cost solutions to keeping likely warming to 1.5°C or 2°C in 2100. Under some scenarios considered in this report, the models indicate that renewable energy may scale up by 3-4 times, and carbon capture and storage capacity by 20 to more than 300 times in the next 30 years. In 2050, across the model runs, assumed negative emissions represent half to more than double the level of positive CO_2 emissions from energy, transport, and industrial processes. The models project significant increases in the global demand for electricity by 2050—in some scenarios, twice as much as current levels, due to a shift toward electrification, or the substitution of electricity for fossil fuel use in engines, furnaces, and other devices. The models indicate that the energy intensity (energy per unit of GDP) of the world economy would decline by roughly one-quarter to more than one-third in the 1.5°C- or 2°C-consistent scenarios compared to the baseline in 2050. However, the IAMs have limitations in foreseeing what technologies may become available and economically viable in the future. There are other possible energy futures if other factors besides costs and technical potential are taken into consideration.

Role of Integrated Assessment Models (IAMs) in Policymaking

The projections and comparative results from the IAM scenarios may provide a foundation for Members of Congress who are considering climate change mitigation proposals. While not without criticism and limitations, the scenarios have been specifically designed to find technology deployments that meet specified climate or emissions constraints, typically in a lowest-cost manner. One strength of IAMs is the ability to explore complex linkages and tradeoffs across energy, agriculture, and land-use sectors that may occur with policy changes. IAMs are most useful not for precise estimates of the future technology or fuel mix under different scenarios, but rather to compare relative results from different policy options.

If Members of Congress are interested in understanding GHG emissions choices, including net-zero emissions, model results from IAMs can inform policy deliberations on possible GHG reduction targets, timing, and pathways. IAMs may help in the consideration of legislative options, such as incentives to accelerate development and deployment of technologies to meet emissions objectives. IAM results suggest that key technologies are in such areas as renewable energy, energy efficiency, electrification, nuclear energy, carbon capture and storage, and carbon removal, among others.

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Introduction

The use of scenario analysis began with military planning and gaming and moved into the business world by the early 1960s as a way to analyze in a systematic way the long-term consequences of strategic decisions.[1] The goal of scenario analysis is neither to predict nor forecast, but rather explore possible futures in order to understand uncertainties and key variables and aid in decisionmaking.

Greenhouse gas (GHG) emissions scenarios are fundamental to understanding the long-term implications of both future anthropogenic climate change[2] and policy options to mitigate it. GHG emissions scenarios are plausible emissions futures based on socioeconomic, environmental, and technological trends and drivers.[3] They are used as inputs in climate models to explore how changes in GHG concentrations alter the earth's radiative balance[4] and thus affect the global climate.[5]

As Congress considers whether and how to address climate change, and particularly legislation drafted with a policy objective to mitigate GHG emissions, Members may have emissions scenarios as evaluations of their options. Moreover, President Biden has announced a number of climate change targets in the Nationally Determined Contribution (NDC) submitted on April 21, 2021, to the United Nations Framework Convention on Climate Change (UNFCCC) as part of the Paris Agreement.[6] The NDC includes a 50% reduction in GHG emissions by 2030 (compared to 2005) and net-zero emissions by 2050.[7] Congress may find it useful to better understand the models that the Administration may use to evaluate and present its strategies. These models can inform deliberations on the feasibility of achieving various emissions reduction trajectories and help to identify policies and tradeoffs, such as competition for land, in meeting those emissions constraints.

This report provides background on emissions scenarios, some of the main economic-energy models that have been used to construct emissions scenarios as part of the Intergovernmental Panel on Climate Change (IPCC) and national policy processes (including those of the United States), and some of the key findings of the scenarios consistent with keeping mean global warming to 1.5°C or 2°C. The report then concludes with observations for Congress.

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[1] Richard H. Moss et al., "The Next Generation of Scenarios for Climate Change Research and Assessment," *Nature*, vol. 463, no. 7282 (February 11, 2010), pp. 747-756; Eric V. Larson, *Force Planning Scenarios, 1945–2016: Their Origins and Use in Defense Strategic Planning*, Santa Monica, CA: RAND Corporation, 2019.

[2] For a discussion of the scientific understanding and confidence regarding the drivers of recent global climate change, see CRS Report R45086, *Evolving Assessments of Human and Natural Contributions to Climate Change*, by Jane A. Leggett.

[3] Hereinafter referred to simply as *emissions scenarios*. Richard H. Moss et al., "The Next Generation of Scenarios for Climate Change Research and Assessment," *Nature* 463, no. 7282 (February 11, 2010), pp. 747-756, https://doi.org/10.1038/nature08823; Aurore Colin, Charlotte Vailles, and Romain Hubert, "Understanding Transition Scenarios: Eight Steps for Reading and Interpreting These Scenarios," I4CE: Institute for Climate Economics, November 2019.

[4] The *radiative balance* is the difference between solar irradiance (sun's energy entering the atmosphere) and energy radiated back to space.

[5] For more discussion of the drivers of climate change, see U.S. Environmental Protection Agency, "Climate Change Science," May 12, 2017, at https://archive.epa.gov/epa/climate-change-science/causes-climate-change.html; R. K. Pachauri et al., *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, eds. R. K. Pachauri and L. Meyer (Geneva, Switzerland: IPCC, 2014).

[6] U.S. Government, "Nationally Determined Contribution. Reducing Greenhouse Gases in the United States: A 2030 Emissions Target," April 21, 2021, at https://www4.unfccc.int/sites/ndcstaging/PublishedDocuments/United%20States%20of%20America%20First/United%20States%20NDC%20April%2021%202021%20Final.pdf.

[7] For a discussion of net-zero emissions, see CRS In Focus IF11821, *Net-Zero Emissions Pledges: Background and Recent Developments*, by Michael I. Westphal.

Economic, Energy, and Climate Modeling: Use of Integrated Assessment Models (IAMs)

Overview

The construction of GHG emissions scenarios is generally done with quantitative models, which are abstractions, or simplified representations of reality. Models capture the essence of the relationships in a system, but are reduced in their complexity to allow one to gain insights not possible simply from available information.[8] Models are often mathematical in nature, but not necessarily so. Best practices for modeling include clearly stated assumptions and transparent relationships among model variables.[9]

Integrated assessment models (IAMs) are a prominent type of economic-energy model that combine elements of the human system (e.g., population, economy, and energy use) and the biophysical earth system into one modeling framework.[10] There are two basic types of IAMs: (1) relatively simple IAMs[11] that incorporate economic damages from climate change but have fairly limited representations of the economy and are highly spatially aggregated,[12] and (2) detailed, higher-spatial-resolution, process-based IAMs that represent the drivers and processes of change in global energy and sometimes land use systems linked to the broader economy, but typically lack a comprehensive representation of climate impacts (e.g., changes in gross domestic product [GDP] from physical climate impacts).[13] The focus of this report is on the latter process-based type of IAMs, which are discussed below in detail.

While one could use various models to generate emissions scenarios,[14] analyses from these more detailed, process-based IAMs have been a key component of the mitigation working group (Working Group III) of the IPCC, the main international scientific body for assessing global climate change.[15] They have also been used in a number of countries' scenarios for decarbonization—for

[8] Katy Borner et al., "An Introduction to Modeling Science: Basic Model Types, Key Definitions, and a General Framework for the Comparison of Process Models," in *Understanding Complex Systems*, 2012.

[9] Katy Borner et al., "An Introduction to Modeling Science: Basic Model Types, Key Definitions, and a General Framework for the Comparison of Process Models," in *Understanding Complex Systems*, 2012.

[10] James A. Edmonds et al., "Integrated Assessment Modeling (IAM)," in *Encyclopedia of Sustainability Science and Technology*, ed. Robert A. Meyers (New York, NY: Springer New York, 2012), pp. 5398-5428.

[11] These include the DICE, PAGE, and FUND models. William Nordhaus, "Evolution of Modeling of the Economics of Global Warming: Changes in the DICE Model, 1992-2017," *Climatic Change*, vol. 148, no. 4 (June 2018), pp. 623-640, at https://doi.org/10.1007/s10584-018-2218-y; David Anthoff and Richard S. J. Tol, *The Climate Framework for Uncertainty, Negotiation, and Distribution (FUND), Technical Description, Version 3.9*, 2014; C. W. Hope, *The PAGE09 Integrated Assessment Model: A Technical Description*, Judge Business School, University of Cambridge, 2011.

[12] They are spatially aggregated in that they typically operate at no smaller than the country-scale. They have been used to calculate the *social cost of carbon*, a monetary estimate of the discounted climate change impacts to society over time from an additional ton of carbon dioxide. See Delavane Diaz and Frances Moore, "Quantifying the Economic Risks of Climate Change," *Nature Climate Change*, vol. 7, no. 11 (November 2017), pp. 774-782 ; CRS In Focus IF10625, *Social Costs of Carbon/Greenhouse Gases: Issues for Congress*, by Jane A. Leggett.

[13] These are called *process-based* because they offer a detailed representation of the energy system, including energy demand, future extraction, transformation, distribution, and use of energy and explore linkages with other sectors in the economy, such as agriculture and land use. They have a higher spatial resolution in that they incorporate features at finer spatial scales than the country-scale (for example, agro-ecological zones or hydrologic basins).

[14] For an example of a web-based emissions scenario tool, see Energy Policy Simulator: Energy Innovation, "Energy Policy Solutions," at https://www.energypolicy.solutions/.

[15] For a review of some of the main conclusions from the IPCC assessment reports over time, see CRS Report R45086,

example, the U.S. midterm strategy for deep decarbonization developed during the Obama Administration.[16]

These detailed, process-based IAMs[17] are numerical, computer models. They vary considerably in their sectoral (e.g., transportation, power generation, industry), technological, or macroeconomic detail; geographic representation; availability of technologies and mitigation options; economic structure; and solution approach (**Appendix A**).[18] However, they are typically structured to include several principal building blocks, or modules (**Figure 1**):[19]

- **Macroeconomy System.** This module uses outside ("exogenous" to the model) macroeconomic inputs (e.g., population, labor productivity, sometimes GDP) to estimate energy demands for each sector and world region. The most common sectors include transport, buildings, industry, and agriculture.
- **Energy System.** This module typically includes a representation of the sources of primary energy[20] supply, modes of energy transformation (e.g., combustion of fossil fuels into heat and electricity), and energy service demands (e.g., passenger and freight transport, industry energy use, residential and commercial heating and electricity). This building block allows the model to choose a wide range of fuels and technologies to meet the energy demands and represents the costs and performance (efficiency, lifetime) of the energy technologies.[21] It would include energy supply technologies (e.g., fossil fuels, nuclear, solar photovoltaics, wind), as well as energy demand technologies (e.g., gas stoves and boilers, electric heat pumps, internal combustion and electric vehicles, blast furnaces). This module could also include energy demand from agriculture and water systems. The fuels used to meet energy demand in each time period have associated emissions factors that relate fuel combustion to greenhouse gas emissions. Many IAMs also represent the nonenergy sectors, such as land use and agriculture, and include noncombustion CO_2, and non-CO_2 GHGs, such as methane and nitrous dioxide. The ways in which IAMs "choose" technologies and fuels vary with model structure and the criteria or "objective functions" that the modelers specify, and these can explain many differences across model results.
- **Climate System.** This module relates emissions over any time period to changes in atmospheric concentrations of GHGs and the resulting changes in earth's mean

Evolving Assessments of Human and Natural Contributions to Climate Change, by Jane A. Leggett

[16] The White House, "United States Mid-Century Strategy for Deep Decarbonization," November 2016, at https://unfccc.int/files/focus/long-term_strategies/application/pdf/mid_century_strategy_report-final_red.pdf.

[17] Henceforth, these detailed, process-based IAMs will simply be referred to as *IAMs*.

[18] Integrated Assessment Modelling Consortium, "IAMC Wiki," 2020, at https://www.iamcdocumentation.eu/index.php/IAMC_wiki.

[19] Ajay Gambhir et al., "A Review of Criticisms of Integrated Assessment Models and Proposed Approaches to Address These, Through the Lens of BECCS," *Energies*, vol. 12, no. 9 (May 1, 2019), pp. 1-21; Joint Global Change Research Institute, "GCAM v4.3 Documentation," at https://jgcri.github.io/gcam-doc/.

[20] *Primary energy* is energy found in nature and not subject to any human conversion process. Primary energy includes fossil fuels (petroleum, natural gas, and coal), nuclear energy, and renewable sources of energy, such as wind and solar. *Secondary energy* refers to resources that have been converted (for example, crude oil that is refined into fuels, coal that is used in a coal-fired plant to generate electricity, or wind that is harnessed by a turbine to generate electricity).

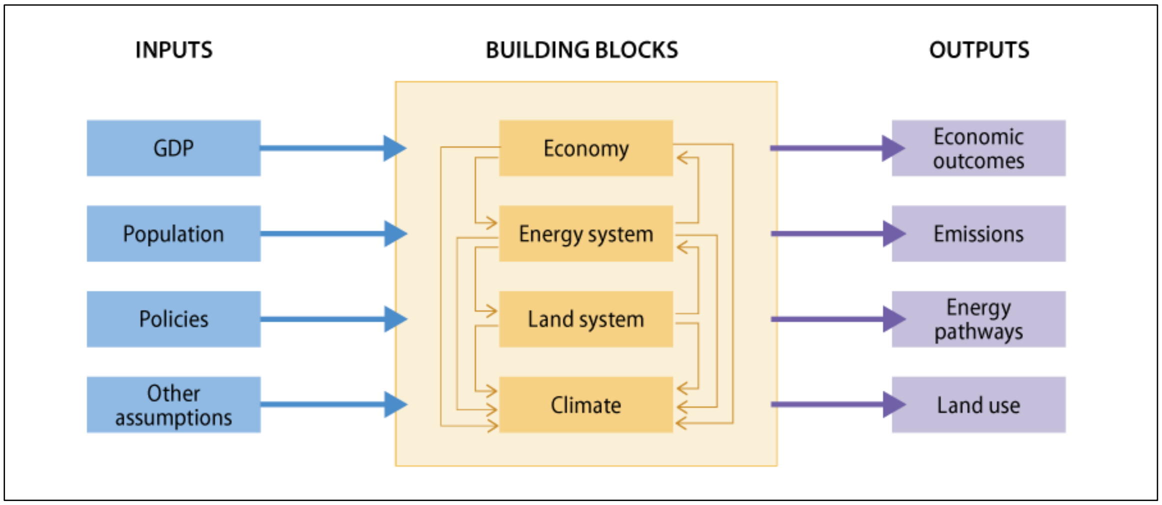
[21] Models very greatly in the amount of technological detail they contain. This can greatly affect the options available in the model for responding to policy constraints, and ultimately the results from the model.

surface temperature. Some IAMs include reduced-form global climate carbon-cycle models that include feedbacks among the atmosphere, soil, and oceans.[22]

One key distinction among IAMs is how they structure the economy. Equilibrium in economic theory is reached when prices are found to match supply and demand in a market. *General equilibrium* models represent the entire economy (though the sectoral detail could vary significantly) and find a set of prices that have the effect of "clearing" all markets simultaneously. *Partial equilibrium* models do so for just one or a couple of markets/sectors (e.g., energy, agriculture), assuming prices in other markets remain constant.[23]

All IAMs generally are designed to meet some emissions limit or climate threshold in a *cost-effective* manner.[24] They vary in how they represent costs and whether they simulate future emissions and technology paths, or whether they *optimize* them over time (i.e., least-cost pathway), assuming perfect foresight.[25] IAMs are often used to compare a *baseline scenario*[26]—an emissions trajectory under current conditions/policies—with a *policy scenario*, where climate policies, targets, constraints, or changes in the technology availability, cost, and mix are explored.

Figure 1. Illustrative Example of IAM Inputs, Building Blocks, and Outputs



Source: Adapted from CarbonBrief, "Q&A: How 'Integrated Assessment Models' Are Used to Study Climate Change," February 10, 2018, at https://www.carbonbrief.org/qa-how-integrated-assessment-models-are-used-to-study-climate-change.

Note: IAMs vary in how they incorporate socioeconomics (for example, population and labor productivity may be used to generate GDP estimates) and their sectoral representation.

[22] GCAM, for example, has a global climate carbon-cycle model, Hector, that models carbon flux in the atmosphere, three "pools" on land, and four "pools" in the ocean. Joint Global Change Research Institute, "GCAM v5.3 Documentation: Earth System Module – Hector v2.0," at http://jgcri.github.io/gcam-doc/gcam-usa.html.

[23] Elizabeth A. Stanton, Frank Ackerman, and Sivan Kartha, "Inside the Integrated Assessment Models: Four Issues in Climate Economics," *Climate and Development*, vol. 1, no. 2 (2009), pp. 166-184.

[24] Ajay Gambhir et al., "A Review of Criticisms of Integrated Assessment Models and Proposed Approaches to Address These, through the Lens of BECCS," *Energies*, vol. 12, no. 9 (May 1, 2019), pp. 1-21.

[25] Elizabeth A. Stanton, Frank Ackerman, and Sivan Kartha, "Inside the Integrated Assessment Models: Four Issues in Climate Economics," *Climate and Development*, vol. 1, no. 2 (2009), pp. 166-184.

[26] Aurore Colin, Charlotte Vailles, and Romain Hubert, "Understanding Transition Scenarios: Eight Steps for Reading and Interpreting These Scenarios," I4CE: Institute for Climate Economics, November 2019.

IAMs and the IPCC Assessment Process

The IPCC has used emissions scenarios since its First Assessment Report in 1990, which presented a set of four scenarios—a baseline *business as usual* scenario and three policy scenarios.[27] In 1992, the IPCC reformulated the scenarios to include only no-climate-policy scenarios, spanning a range of six plausible pathways, relying on internally coherent assumptions about how economies and technologies may evolve.[28] By 2000, the IPCC had developed the quantitative Special Report on Emissions Scenarios (SRES) scenarios with four narrative storylines of population, economic growth, and GHG emissions scenarios.[29] When the IPCC revised the scenarios in the late 2000s, the IPCC decided to separate the development of socioeconomic storylines from scenarios of global warming that could occur by the end of the century, in order to speed up the climate modeling process.[30] This led to development of Representative Concentration Pathways (RCPs) and associated Shared Socioeconomic Pathways (SSPs).

Scenarios of Global Warming and Socioeconomic Storylines

In response to a call from the IPCC for a research organization to lead the integrated assessment modeling community in the development of new scenarios, the Integrated Assessment Modeling Consortium (IMAC)[31] was established in 2007. The IMAC developed the RCPs—scenarios that represent different target levels in 2100 of *radiative forcing*,[32] or how the earth's energy imbalance may change due to various climatic drivers, such as GHG concentrations in the atmosphere or reflectivity of the earth's surface. These RCP scenarios are used in analyses by global climate models[33] to understand the impact of changing radiative forcing on global and regional climate.[34] For example, climate change projections made using the IPCC RCPs have been used in analyses as part of the U.S. Fourth National Climate Assessment.[35]

The RCPs are in units of watts per meter squared (W/m^2), a measure of the energy at the top of the atmosphere.[36] Higher values indicate greater forcing. Thus, RCPs can be considered a proxy for

[27] Richard H. Moss et al., "The Next Generation of Scenarios for Climate Change Research and Assessment," *Nature*, vol. 463, no. 7282 (February 11, 2010), pp. 747-756.

[28] Jane Leggett et al., "Emissions Scenarios for IPCC: An Update," in *Climate Change 1992. The Supplementary Report to the IPCC Scientific Assessment*, Intergovernmental Panel on Climate Change, 1992, https://www.ipcc.ch/site/assets/uploads/2018/05/ipcc_wg_I_1992_suppl_report_section_a3.pdf.

[29] N. Nakicenovic et al., *Special Report on Emissions Scenarios (SRES), A Special Report of Working Group III of the Intergovernmental Panel on Climate Change* (Cambridge: Cambridge University Press, 2000).

[30] Richard H. Moss et al., "The Next Generation of Scenarios for Climate Change Research and Assessment," *Nature*, vol. 463, no. 7282 (February 11, 2010), pp. 747-756.

[31] The Integrated Assessment Modeling Consortium, at http://www.iamconsortium.org.

[32] *Radiative forcing* is the difference between solar irradiance (sun's energy entering the atmosphere) and energy radiated back to space. For more discussion of the drivers of climate change, see U.S. Environmental Protection Agency, "Climate Change Science," May 12, 2017, at https://archive.epa.gov/epa/climate-change-science/causes-climate-change.html.

[33] Intergovernmental Panel on Climate Change, "What Is a GCM?" Data Distribution Centre, accessed April 19, 2021, at https://www.ipcc-data.org/guidelines/pages/gcm_guide.html.

[34] Discussion of climate models is beyond the scope of this report. One major project to compare and continually improve climate models is the World Climate Research Program, "Coupled Model Intercomparison Project (CMIP)," at https://www.wcrp-climate.org/wgcm-cmip.

[35] C. W. Avery et al., "Data Tools and Scenario Products," in *In Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment*, vol. II (Washington, DC: U.S. Global Change Research Program, 2018), pp. 1413-1430.

[36] Watt is a unit of energy, so radiative forcing (W/m^2) is a measure of energy per unit area.

mean global temperatures. The initial four RCPs spanned the range of radiative forcing values for the year 2100 found in the peer-reviewed literature at the time (i.e., from 2.6 to 8.5 W/m^2); see **Table 1**.[37] The IPCC Fifth Assessment Report focused on the four RCPs listed in **Table 1**; subsequently, RCP 1.9, RCP 3.4, and RCP 7.0 have been added for the Sixth Assessment Report, due to be published beginning in 2021.

In IPCC parlance, *likely* refers to at least a 66% probability.[38] RCP 2.6 indicates a likely 2100 temperature range of 0.3°C to 1.7°C (mean 1.0°C) above preindustrial levels.[39] RCP 2.6 is consistent with keeping likely mean global warming to 2°C (with at least a 66% probability) in 2100.[40] RCP 4.5 indicates a likely 2100 temperature range of 1.1°C to 2.6°C (mean 1.8°C). In contrast, the radiative forcing of RCP 8.5 could result in an increase in warming of nearly 5°C (mean of 3.7ºC and likely range 2.6ºC to 4.8ºC) above preindustrial levels by the end of the century.[41] Recently, there has been some criticism of RCP 8.5, with some groups saying it is not very plausible;[42] for example, reaching it would mean policy choices leading to a five-fold increase in global coal use, which may be larger than estimates of recoverable reserves.[43] The new RCP 1.9 is consistent with limiting the increase in global mean temperature in 2100 to 1.5°C with approximately a 66% probability.[44]

Table 1. Overview of the RCPs

RCP	Description	Temperature Increase (2081-2100) (°C)
RCP 2.6	Peak in radiative forcing at ~3 W/m^2 (~490 ppm CO_2 eq) before 2100 and then decline (the selected pathway declines to 2.6 W/m^2 by 2100)	0.3 to 1.7 (mean 1.0)
RCP 4.5	Stabilization without overshoot pathway to 4.5 W/m^2 (~650 ppm CO_2 eq) at stabilization after 2100	1.1 to 2.6 (mean 1.8)

[37] Detlef P. van Vuuren et al., "The Representative Concentration Pathways: An Overview," *Climatic Change*, vol. 109, no. 1-2, SI (November 2011), pp. 5-31.

[38] IPCC, "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* (Cambridge, UK: Cambridge University Press, 2013).

[39] Table 2.1 in IPCC, "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* (Cambridge, UK: Cambridge University Press, 2013). Each RCP results in a range of temperatures in 2100. See also Table 1 in Detlef P. van Vuuren et al., "The Representative Concentration Pathways: An Overview," *Climatic Change*, vol. 109, no. 1-2, SI (November 2011), pp. 5-31.

[40] IPCC, "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* (Cambridge, UK: Cambridge University Press, 2013).

[41] Matthew J. Gidden et al., "Global Emissions Pathways under Different Socioeconomic Scenarios for Use in CMIP6: A Dataset of Harmonized Emissions Trajectories Through the End of the Century," *Geoscientific Model Development*, vol. 12, no. 4 (April 12, 2019), pp. 1443-1475.

[42] Zeke Hausfather and Glen P. Peters, "Emissions: The 'Business as Usual' Story Is Misleading," *Nature*, vol. 577, no. 7792 (January 30, 2020), pp. 618-620.

[43] Justin Ritchie and Hadi Dowlatabadi, "The 1000 GtC Coal Question: Are Cases of Vastly Expanded Future Coal Combustion Still Plausible?" *Energy Economics*, vol. 65 (2017), pp. 16-31.

[44] Joeri Rogelj et al., "Scenarios Towards Limiting Global Mean Temperature Increase below 1.5 °C," *Nature Climate Change*, vol. 8, no. 4 (April 1, 2018), pp. 325-332.

RCP	Description	Temperature Increase (2081-2100) (°C)
RCP 6	Stabilization without overshoot pathway to 6 W/m² (~850 ppm CO_2 eq) at stabilization after 2100	1.4 to 3.1 (mean 2.2)
RCP 8.5	Rising radiative forcing pathway leading to 8.5 W/m² (~1370 ppm CO_2 eq) by 2100	2.6 to 4.8 (mean 3.7)

Source: Detlef P. van Vuuren et al., "The Representative Concentration Pathways: An Overview," *Climatic Change* 109, no. 1-2, SI (November 2011), pp. 5-31, at https://doi.org/10.1007/s10584-011-0148-z; IPCC, "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* (Cambridge, UK: Cambridge University Press, 2013).

Note: The temperature increases are based on 5% to 95% of model ranges.

The RCPs are complemented by SSPs, which are socioeconomic narratives of the future. While the RCPs effectively set representative pathways for GHG concentrations and indicate likely end-of-the-century warming, the SSPs indicate how society may transform and, consequently, how GHG emissions may change over time. There are five SSPs, designed to span possible societal futures and cover the societal trends that could make both climate change mitigation and adaptation more or less challenging to undertake:

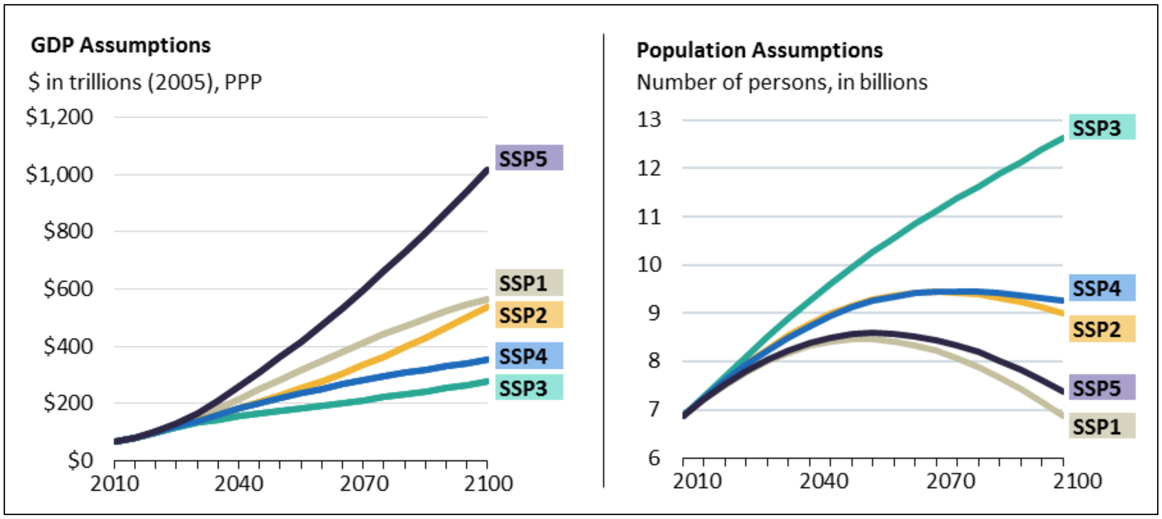
1. SSP1 ("Sustainability—Taking the Green Road");
2. SSP2 ("Middle of the Road");
3. SSP3 ("Regional Rivalry—A Rocky Road");
4. SSP4 ("Inequality—A Road Divided"); and
5. SSP5 ("Fossil-Fueled Development—Taking the Highway").[45]

The SSPs vary considerably in what they assume about economic growth, inequality, trade, dependence on fossil fuels, and material consumption (see **Appendix B** for more details). For example, SSP1 assumes medium economic growth, moderate international trade, low growth in material consumption, low-meat diets, and an emphasis on renewable energy and energy efficiency, while SSP5 assumes high economic growth, high international trade, high material consumption, meat-rich diets, and a focus on the use of fossil fuels. They vary considerably in their trajectories for two important socioeconomic variables: GDP and population (**Figure 2**). In 2100, global GDP for SSP1 and SSP5 ranges from about $280 billion to $1,000 billion ($1 quadrillion), while population ranges from 6.9 billion to 12.6 billion in 2100, respectively. Some of the authors have characterized SSP2 as a "world that continues the historical experience."[46]

[45] Keywan Riahi et al., "The Shared Socioeconomic Pathways and Their Energy, Land Use, and Greenhouse Gas Emissions Implications: An Overview," *Global Environmental Change*, vol. 42 (January 2017), pp. 153-168; Brian C. O'Neill et al., "The Roads Ahead: Narratives for Shared Socioeconomic Pathways Describing World Futures in the 21st Century," *Global Environmental Change*, vol. 42 (January 2017), pp. 169-180.

[46] Joeri Rogelj et al., "Scenarios Towards Limiting Global Mean Temperature Increase Below 1.5 °C," *Nature Climate Change*, vol. 8, no. 4 (April 1, 2018), pp. 325-332.

Figure 2. SSPs and Population and GDP Assumptions



Source: CRS analysis of data from International Institute for Applied Systems Analysis, "SSP Database (Shared Socioeconomic Pathways) - Version 2.0," at https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=10; International Institute for Applied Systems Analysis, "SSP Database (Shared Socioeconomic Pathways) - Version 2.0," at https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=10; Keywan Riahi et al., "The Shared Socioeconomic Pathways and Their Energy, Land Use, and Greenhouse Gas Emissions Implications: An Overview," *Global Environmental Change*, vol. 42 (January 2017), pp. 153-168.

Notes: There are different interpretations of the SSP socioeconomic variables. This projection for GDP was provided by the Organization for Economic Co-operation and Development (OECD). GDP is in purchasing power parity (PPP), $2005. This projection for population was provided by the International Institute for Applied Systems Analysis-Wittgenstein Centre (IIASA-WIC).

For each SSP, the six IAM groups tried to find a solution that satisfied each RCP future warming scenario, in order to understand how the energy and land-use systems could evolve in the future (**Appendix A**). These SSP-RCP scenarios were then compared to a baseline, which is a reference-case scenario without (1) climate change mitigation policies (no policies after 2010, including those related to the Paris Agreement) and (2) feedbacks from climate change on socioeconomic or natural systems. To be consistent and aid in comparison across IAM results, the IAM groups all used the same climate model to convert from annual GHG emissions to concentrations and estimate resulting global warming.[47]

Results from Emissions Scenarios Consistent with 1.5°C and 2°C Warming

The United States is a party to the UN Framework Convention on Climate Change (UNFCCC),[48] with its objective in Article 2 being

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[47] As **Table 1** shows, the same GHG concentrations could result in different estimated warming. The IAMs used the same climate carbon-cycle model (MAGICC Climate Modeling System, at http://www.magicc.org/) to aid in comparison of IAM results.

[48] U.N. Treaty Collection, Chapter XXIII. 7. President George H. W. Bush transmitted the signed treaty to the Senate for its advice and consent in 138 *Congressional Record* 23902 (September 8, 1992). The U.S. Senate gave its advice and consent to ratification in 138 *Congressional Record* 33527 (October 7, 1992). See also S. Treaty Doc. 102-38 (1992); S. Exec. Rept. 102-55. President Bush signed the instrument of ratification and submitted it to the United Nations on October 13, 1992. Depositary notification C.N.148.1993.

> stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time-frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner.[49]

The Biden Administration rejoined the Paris Agreement,[50] a subsidiary agreement under the UNFCCC.[51] The agreement, with 191 parties as of the date of this publication, includes an aim of strengthening the global response to climate change, including by

> [h]olding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change.[52]

These temperature targets are supported by the scientific consensus that the overall risks to physical, ecological, and social systems (e.g., agricultural production, livelihoods) increase with warming. One consideration is the level of climate change sufficient to trigger abrupt and irreversible changes (*tipping points*). While precise levels remain uncertain, the risk associated with crossing such thresholds increases with rising temperature.[53] The IPCC's assessments of the temperature increase at which certain natural, managed, and human systems could experience at least moderate risks have generally been revised downward over time, given more scientific studies.[54] There is now scientific evidence to suggest that some tipping points could be exceeded between 1°C to 2°C of warming.[55]

While the Paris Agreement aims to achieve temperature goals, there is no specified global emissions target.[56] First, there is uncertainty around *climate sensitivity*,[57] that is, the temperature change projected to result from a change in the concentration of GHGs in the atmosphere. The IPCC Fifth Assessment Report estimated that a doubling of atmospheric CO_2 from preindustrial levels would likely result in an increase in global mean surface temperature in the range of 1.5°C to 4.5°C.[58] The ranges of temperature increase associated with each IPCC RCP (**Table 1**) reflect the

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[49] United Nations Framework Convention on Climate Change, May 9, 1992, S. Treaty Doc No. 102-38, 1771 U.N.T.S. 107.

[50] The White House, "Paris Climate Agreement," January 20, 2021, at https://www.whitehouse.gov/briefing-room/statements-releases/2021/01/20/paris-climate-agreement/.

[51] For more on the Paris Agreement and the UNFCCC, see CRS Report R46204, *The United Nations Framework Convention on Climate Change, the Kyoto Protocol, and the Paris Agreement: A Summary*, by Jane A. Leggett.

[52] United Nations, "Paris Agreement," Article 2.1a, at https://www.un.org/en/climatechange/paris-agreement.

[53] Pachauri et al., *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*.

[54] Timothy M. Lenton et al., "Climate Tipping Points—Too Risky to Bet Against," *Nature*, vol. 575, no. 7784 (November 28, 2019), pp. 592-595.

[55] IPCC, *Global Warming of 1.5°C* (Intergovernmental Panel on Climate Change, 2018); IPCC, *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate* (Intergovernmental Panel on Climate Change, 2019).

[56] For a discussion of the role of anthropogenic GHG emissions in climate change, see CRS Report R45086, *Evolving Assessments of Human and Natural Contributions to Climate Change*, by Jane A. Leggett.

[57] Tapio Schneider et al., "Climate Goals and Computing the Future of Clouds," *Nature Climate Change*, vol. 7, no. 1 (January 1, 2017), pp. 3-5. The term *equilibrium climate sensitivity* is often used. This term refers specifically to the global surface temperature increase that results after CO_2 concentrations have doubled and the climate system has equilibrated to this perturbation.

[58] IPCC, "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* (Cambridge, UK: Cambridge

uncertainty about climate sensitivity. Second, there are many different global emissions pathways that could result in warming that does not exceed 1.5°C/2°C in 2100, and hence there are also different possible trajectories for individual countries. Many IAMs find a "least-cost" pathway globally for achieving a specific temperature target, or impose other constraints, but policymakers and stakeholders may consider other factors to be important, such as feasibility, capabilities of different countries, and equity.[59]

Given countries' commitments to the Paris Agreement's temperature goals, the remainder of this section analyzes IAM emissions scenarios consistent with warming of 1.5°C to 2°C by 2100.

Methodology for Scenario Selection

The IAMC, as part of its ongoing cooperation with the IPCC's Working Group III on mitigation, issued a call for submissions of scenarios that limit warming to 1.5°C or 2°C in the "long term" (e.g., 2100) for inclusion in the IPCC *Global Warming of 1.5°C* report.[60] In total, 19 modeling groups submitted 529 scenarios, of which 90 were consistent with 1.5°C, and 132 were consistent with 2°C. [61]

However, the modeling scenarios differ in their socioeconomic assumptions, and not all have model outputs that are publicly available. This section of the report examines the results from the six IAM groups that have modeled the SSP-RCP scenarios. All of these IAMs used a consistent set of socioeconomic assumptions and have model outputs available in the SSP public database, hosted by the International Institute for Applied Systems Analysis (IIASA).[62] These IAM modeling scenarios will be a focus of the forthcoming IPCC Sixth Assessment Report. This report does not examine other non-IAMC scenarios that may be compatible with 1.5°C or 2°C mean global warming. [63]

RCP 1.9 and RCP 2.6 can be considered proxies for 1.5°C and 2°C pathways.[64] As noted above, RCP 2.6 is consistent with keeping *likely*[65] mean global warming in 2100 to 2°C above preindustrial levels,[66] while RCP 1.9 is consistent with keeping *likely* mean global warming to 1.5°C above

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University Press, 2013).

[59] Yann Robiou du Pont et al., "Equitable Mitigation to Achieve the Paris Agreement Goals (Vol 7, Pg 38, 2017)," *Nature Climate Change*, vol. 7, no. 2 (February 2017). p. 153, at https://doi.org/10.1038/NCLIMATE3210.

[60] P. Forster et al., "2.SM Mitigation Pathways Compatible with 1.5°C in the Context of Sustainable Development—Supplementary Material," in *Global Warming of 1.5 °C* (Intergovernmental Panel on Climate Change, 2018); J. Rogelj et al., "Chapter 2: Mitigation Pathways Compatible with 1.5°C in the Context of Sustainable Development," in *Global Warming of 1.5 °C* (Intergovernmental Panel on Climate Change, 2018).

[61] The term *1.5°C-/2°C-consistent* refers to pathways with no overshoot, with limited (low) overshoot, and with high overshoot of 1.5°C-/2°C in 2100. J. Rogelj et al., "Chapter 2: Mitigation Pathways Compatible with 1.5°C in the Context of Sustainable Development," in *Global Warming of 1.5 °C* (Intergovernmental Panel on Climate Change, 2018).

[62] International Institute for Applied Systems Analysis, "SSP Database (Shared Socioeconomic Pathways) - Version 2.0," at https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=10; Keywan Riahi et al., "The Shared Socioeconomic Pathways and Their Energy, Land Use, and Greenhouse Gas Emissions Implications: An Overview," *Global Environmental Change*, vol. 42 (January 2017), pp. 153-168.

[63] These include the International Energy Agency, research and consulting firms (e.g., Bloomberg New Energy Finance, McKinsey), and a number of oil majors (e.g., BP, Shell, Equinor); Aurore Colin, Charlotte Vailles, and Romain Hubert, "Understanding Transition Scenarios: Eight Steps for Reading and Interpreting These Scenarios," I4CE: Institute for Climate Economics, November 2019.

[64] Joeri Rogelj et al., "Scenarios Towards Limiting Global Mean Temperature Increase Below 1.5 °C," *Nature Climate Change*, vol. 8, no. 4 (April 1, 2018), pp. 325-332.

[65] *Likely* in IPCC parlance refers to at least a 66% probability.

[66] IPCC, "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* (Cambridge, UK: Cambridge

preindustrial levels in 2100.[67] The six IAMs all used the same climate model, Model for the Assessment of Greenhouse Gas Induced Climate Change (MAGICC). For RCP 1.9, the range in the increase in mean annual temperature in 2100 was estimated to be 1.3°C to 1.4°C, and for RCP 2.6, 1.7°C to 1.8°C in 2100.[68] For RCP 1.9, all the IAMs do "overshoot" the 1.5°C temperature target in the 2040s.[69] For two of the six IAMs, SSP2-RCP1.9 was "infeasible," meaning they could not find a solution that avoided a 1.5ºC increase.[70] Throughout the rest of the report, the RCP 1.9 and RCP 2.6 are referred to as *1.5ºC-consistent* and *2ºC-consistent* scenarios, respectively.

The SSP database includes the SSP-RCP and baseline scenarios and provides outputs (2005-2100) for a number of variables, such as primary, secondary, and end-use energy; land cover; agricultural demand and production; GHG emissions; and climate (radiative forcing, temperature). This section discusses global results, because the SSP database does not break out the data to the national scale. Given the size of the U.S. economy and its contribution to GHG emissions, the same basic conclusions from the global results may be instructive for technology deployments in the United States consistent with meeting the global 1.5°C or 2°C targets. The focus of this section is an analysis of some (but not all) of the key results for the *middle-of-the-road* SSP2 socioeconomic scenario, referred to as a "world that continues the historical experience."[71] Given the large number of possible combinations of SSP-RCP scenarios, IAMs, and output variables, a comprehensive analysis of other scenarios and results is beyond the scope of this report. This section, in particular, highlights a number of key results related to energy use and negative emissions technologies.

The focal year for the analysis is 2050, which is far enough in the future to discern differences between the 1.5°C-/2°C-consistent scenarios and the baseline. Modeling results beyond this time frame may be instructive, but uncertainties increase further into the future—for example, regarding the cost and availability of various technologies.

Primary Energy Use

The IAMs provide results on future energy use under the different SSP-RCP scenarios. The results from the six IAMs show significant differences in the modeled future energy mix, even with the same socioeconomic assumptions (**Figure 3**). This is due to not only differences in model structure and solution approach, but also the availability and costs of technologies and fuels. In the baseline (no climate policy) scenario, all the models generally project a world dominated by fossil-fuel use. Fossil fuels provide more than 80% of primary energy use across the IAMs in the baseline scenarios.

University Press, 2013).

[67] Joeri Rogelj et al., "Scenarios Towards Limiting Global Mean Temperature Increase Below 1.5 °C," *Nature Climate Change*, vol. 8, no. 4 (April 1, 2018), pp. 325-332.

[68] International Institute for Applied Systems Analysis, "SSP Database (Shared Socioeconomic Pathways) - Version 2.0," at https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=10; Keywan Riahi et al., "The Shared Socioeconomic Pathways and Their Energy, Land Use, and Greenhouse Gas Emissions Implications: An Overview," *Global Environmental Change*, vol. 42 (January 2017), pp. 153-168.

[69] Institute for Applied Systems Analysis, "SSP Database (Shared Socioeconomic Pathways) - Version 2.0," at https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=10; Keywan Riahi et al., "The Shared Socioeconomic Pathways and Their Energy, Land Use, and Greenhouse Gas Emissions Implications: An Overview," *Global Environmental Change*, vol. 42 (January 2017), pp. 153-168.

[70] Joeri Rogelj et al., "Scenarios Towards Limiting Global Mean Temperature Increase Below 1.5 °C," *Nature Climate Change*, vol. 8, no. 4 (April 1, 2018), pp. 325-332.

[71] Joeri Rogelj et al., "Scenarios Towards Limiting Global Mean Temperature Increase Below 1.5 °C," *Nature Climate Change*, vol. 8, no. 4 (April 1, 2018), pp. 325-332.

The models indicate that keeping global mean temperature increase on a trajectory to below 2°C in 2100 requires a scaling up of nonbiomass renewable energy technologies across the globe in 2050, increasing from between 4% to 10% of primary energy in the baseline scenario to between 10% and 29% in the 2°C-consistent scenarios and 11% to 40% in 1.5°C-consistent scenarios. The lower the radiative forcing target, the greater the increase in renewables for providing primary energy. In comparison, 10% of total primary energy worldwide came from nonbiomass renewables in 2019.[72]

The IAMs indicate a decrease in the share of fossil fuels in the energy mix in 2050 in the 1.5°C- and 2°C-consistent scenarios. Coal in particular would see decreases, providing no more than 10% and 14% of primary energy across IAMs in the 1.5°C- and 2°C-consistent scenarios, respectively, compared to 25% to 35% of primary energy in the baseline. As a point of reference, in 2019, coal provided 26% of global primary energy.[73] The models project an increase in nuclear energy, providing 4% to 12% of primary energy in 2050 in the 2°C-consistent scenario, compared to 1% to 3% in the baseline in 2050 (and 5% today).[74] As will be discussed below, the IAMs vary considerably in how much they rely on biomass to meet energy needs.

Figure 3 also shows that keeping likely warming to 1.5°C and 2°C in 2100 points to reduced primary energy consumption in the modeling scenarios, largely as a result of energy efficiency gains. Compared to the baseline, energy intensity (primary energy per unit of GDP) in 2050 declines 21% to 41% in the 2°C-consistent scenarios and 22% to 32% in 1.5°C-consistent scenarios.[75]

[72] International Energy Agency, "Global Primary Energy Demand by Fuel, 1925-2019," at https://www.iea.org/data-and-statistics/charts/global-primary-energy-demand-by-fuel-1925-2019. 1 MTOE is equivalent to 0.042 EJ.

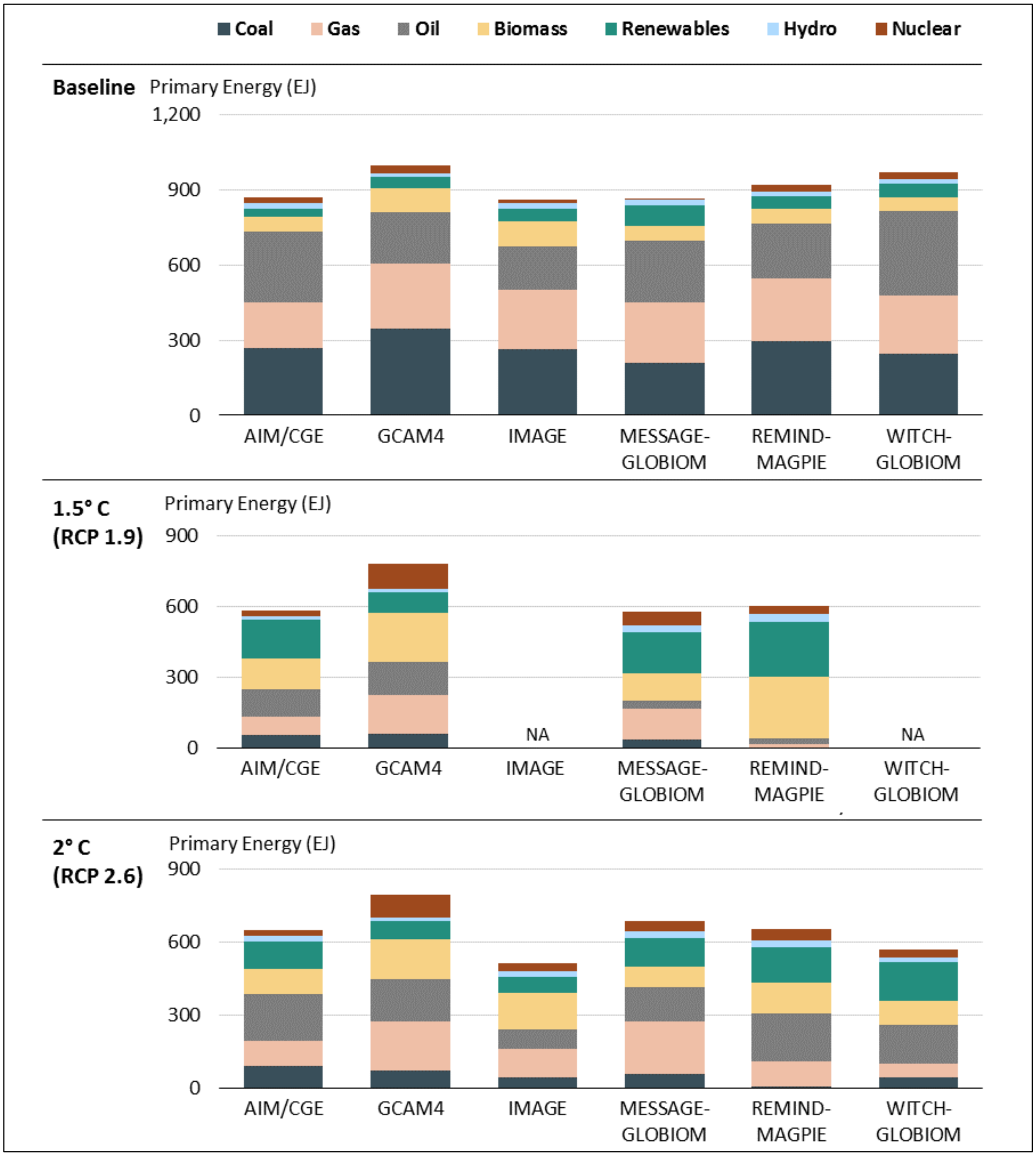
[73] International Energy Agency, "Global Primary Energy Demand by Fuel, 1925-2019," at https://www.iea.org/data-and-statistics/charts/global-primary-energy-demand-by-fuel-1925-2019.

[74] International Energy Agency, "Global Primary Energy Demand by Fuel, 1925-2019," at https://www.iea.org/data-and-statistics/charts/global-primary-energy-demand-by-fuel-1925-2019.

[75] Note that only four of six IAMs had runs for the 1.5°C-consistent scenarios (**Figure 3**). This is reflected in the range differences. CRS analysis of data from International Institute for Applied Systems Analysis, "SSP Database (Shared Socioeconomic Pathways) - Version 2.0," at https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=10; Keywan Riahi et al., "The Shared Socioeconomic Pathways and Their Energy, Land Use, and Greenhouse Gas Emissions Implications: An Overview," *Global Environmental Change*, vol. 42 (January 2017), pp. 153-168.

Figure 3. Global Primary Energy Mix in 2050, by IAM

SSP2 ("middle-of-the-road" socioeconomic scenario)



Source: CRS analysis of data from International Institute for Applied Systems Analysis, "SSP Database (Shared Socioeconomic Pathways) - Version 2.0," at https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=10; Keywan Riahi et al., "The Shared Socioeconomic Pathways and Their Energy, Land Use, and Greenhouse Gas Emissions Implications: An Overview," *Global Environmental Change*, vol. 42 (January 2017), pp. 153-168.

Notes: RCP 2.6 is consistent with keeping mean global warming to 2°C in 2100, while RCP 1.9 is consistent with keeping mean global warming to 1.5°C in 2100. The database includes only four IAMs that could solve for the RCP 1.9 target for the SSP2 scenario. For IMAGE and WITCH models, no solution could be found. Renewables include all nonbiomass renewables (hydro, solar, wind, geothermal, and other).

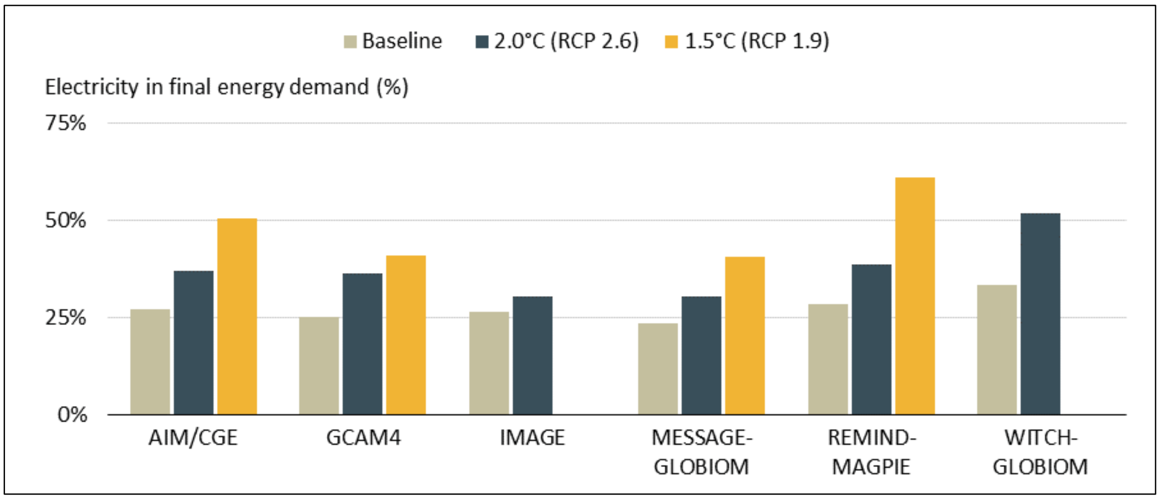
Electrification

Electrification is the substitution of electricity for fossil fuel use in engines, furnaces, and other devices.[76] Climate change studies indicate that electrification is one of the main strategies for decarbonization, along with decarbonization of the power supply (absent carbon capture) and increased energy efficiency (i.e., reduced energy demand).[77]

The IAM results indicate that keeping likely warming to 1.5°C or 2°C in 2100 would entail an increased reliance on electricity to meet energy needs (**Figure 4**). Electricity in final energy demand nearly doubles in most of IAMs in the 1.5°C-consistent scenario compared to the baseline in 2050, reaching 41% to 61% of final energy demand. By comparison, in 2019, electricity comprised 19% of the world's final energy demand.[78]

Figure 4. Global Electrification in 2050, by IAM

SSP2 ("middle-of-the-road" socioeconomic scenario)



Source: CRS analysis of data from International Institute for Applied Systems Analysis, "SSP Database (Shared Socioeconomic Pathways) - Version 2.0," at https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=10; Keywan Riahi et al., "The Shared Socioeconomic Pathways and Their Energy, Land Use, and Greenhouse Gas Emissions Implications: An Overview," *Global Environmental Change*, vol. 42 (January 2017), pp. 153-168.

Notes: RCP 2.6 is consistent with keeping mean global warming to 2°C in 2100, while RCP 1.9 is consistent with keeping mean global warming to 1.5°C in 2100. The database includes only four IAMs that could solve for the RCP 1.9 target for the SSP2 scenario. For IMAGE and WITCH models, no solution could be found.

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[76] Chris Kennedy et al., "Keeping Global Climate Change Within 1.5°C Through Net Negative Electric Cities," *1.5°C Climate Change and Urban Areas* 30 (February 1, 2018), pp. 18-25.

[77] The GHG benefits of electrification depend on the carbon intensity of the electric grid. Except for the most fossil-fuel-intensive grids, electrification will generally result in a net reduction of GHG emissions. (See Chris Kennedy et al., "Keeping Global Climate Change Within 1.5°C Through Net Negative Electric Cities," *1.5°C Climate Change and Urban Areas*, vol. 30 (February 1, 2018), pp. 18-25.) This is due to the fact that electric devices are generally more efficient than fossil fuel devices. For example, electric vehicles are currently two to five times more efficient than internal combustion engines. See IEA, *World Energy Outlook 2020* (Paris, France: International Energy Agency, 2020).

[78] IEA, "Global EV Outlook 2020: Entering the Decade of Electric Drive?" (Paris: International Energy Agency, 2020), at https://www.iea.org/reports/global-ev-outlook-2020.

Peak and Net-Zero CO_2 Emissions

An examination of the global CO_2 emissions over time for all 1.5°C- and 2°C-consistent scenarios reveals several key points policymakers may consider. First, as illustrated in **Figure 5** and **Figure 6**, the IAMs indicate that there are many different global CO_2 emissions pathways that stay within 1.5°C and 2°C in 2100. Second, the models find that the more stringent the radiative forcing target (i.e., RCP output), the earlier the dates for peak and net-zero emissions. In order to keep warming to 2°C in 2100, the models project that annual CO_2 emissions will have to reach net-zero between 2080 and 2100 (**Figure 5**). To achieve a 1.5°C temperature target, the models estimate that CO_2 emissions would have had to peak around 2020 and reach net-zero by 2060 (**Figure 6**).[79] Emissions of other GHGs remain positive in these 1.5°C- and 2°C-consistent scenarios through 2100. According to the models, the later the peak in CO_2 emissions, the sharper the reductions would have to be later in the century to keep within the temperature targets.

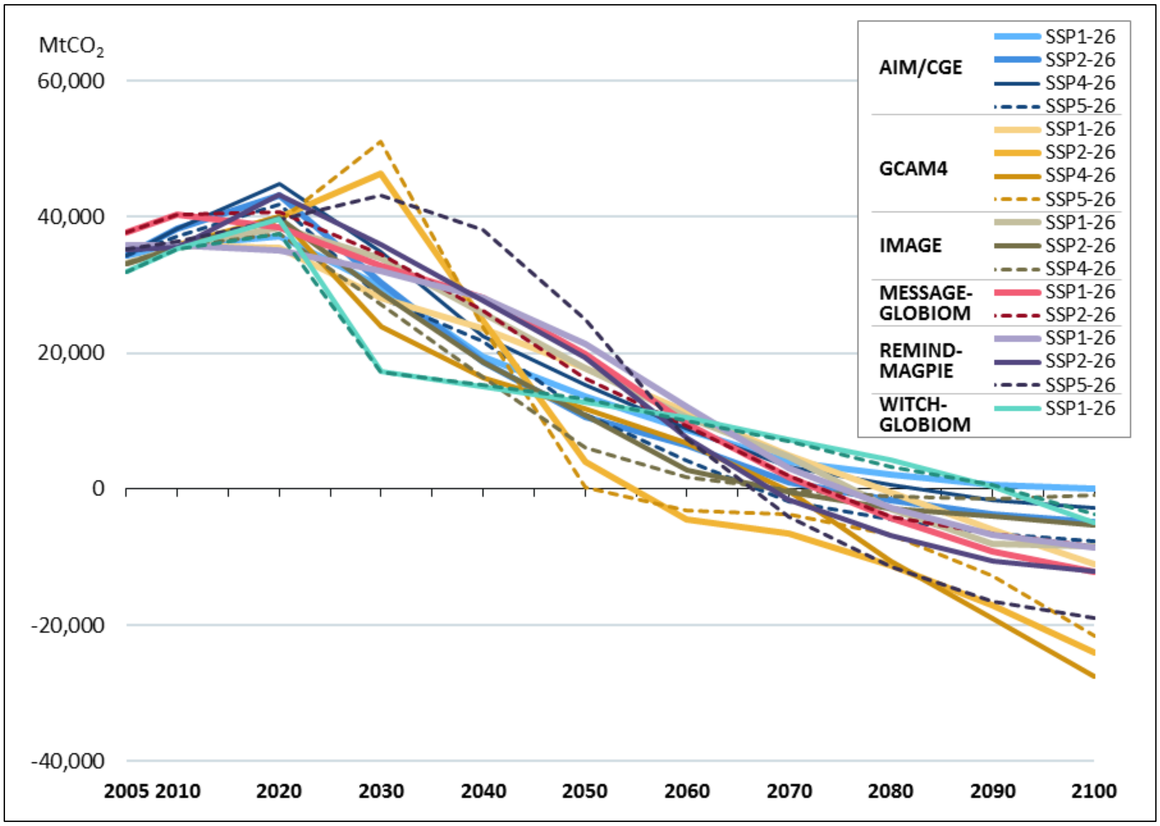
Third, achieving the emissions reductions consistent with meeting the targets in 2100 for both mitigation scenarios generally relies on "negative emissions"[80] (or permanent CO_2 removal, discussed below), though the degree of availability of the technology and reliance on negative emissions technologies vary across IAMs. Carbon removal (i.e., the removal of CO_2 from the atmosphere and storage in geological, terrestrial, or ocean reservoirs, or in products[81]) is needed to balance positive emissions, including those of the other non-CO_2 GHGs.

[79] International Institute for Applied Systems Analysis, "SSP Database (Shared Socioeconomic Pathways) - Version 2.0," at https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=10; Keywan Riahi et al., "The Shared Socioeconomic Pathways and Their Energy, Land Use, and Greenhouse Gas Emissions Implications: An Overview," *Global Environmental Change*, vol. 42 (January 2017), pp. 153-168.

[80] *Negative emissions* refers to the removal of greenhouse gases (GHGs) from the atmosphere by deliberate human activities, in addition to the removals that occur via natural carbon cycle processes. See IPCC, *Global Warming of 1.5°C* (Intergovernmental Panel on Climate Change, 2018).

[81] For a discussion of carbon removal, see CRS In Focus IF11501, *Carbon Capture Versus Direct Air Capture*, by Ashley J. Lawson; and CRS In Focus IF11821, *Net-Zero Emissions Pledges: Background and Recent Developments*, by Michael I. Westphal.

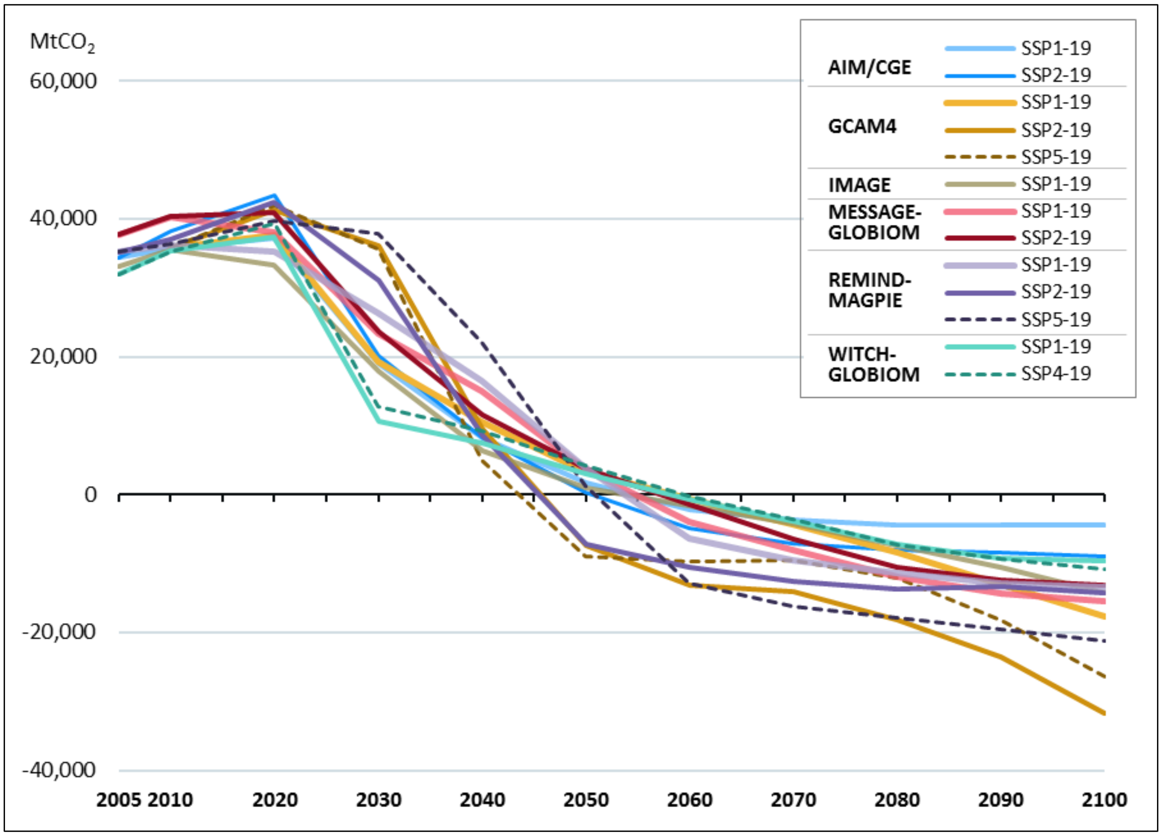
Figure 5. Global CO_2 Emissions over Time Across 2°C-Consistent Scenarios



Source: International Institute for Applied Systems Analysis, "SSP Database (Shared Socioeconomic Pathways) - Version 2.0," at https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=10; Keywan Riahi et al., "The Shared Socioeconomic Pathways and Their Energy, Land Use, and Greenhouse Gas Emissions Implications: An Overview," *Global Environmental Change*, vol. 42 (January 2017), pp. 153-168.

Notes: Each CO_2 trajectory represents one IAM model run for different SSPs. The legend indicates the model name, followed by the socioeconomic scenario (SSP) and radiative forcing (RCP). RCP 2.6 (denoted as "26" in the legend) is consistent with keeping likely mean global warming to 2°C in 2100. RCP 2.6 refers to the radiative forcing target of 2.6 Wm^{-2} radiative forcing in 2100.

Figure 6. Global CO_2 Emissions over Time Across 1.5°C-Consistent Scenarios



Source: International Institute for Applied Systems Analysis, "SSP Database (Shared Socioeconomic Pathways) - Version 2.0," at https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=10; Keywan Riahi et al., "The Shared Socioeconomic Pathways and Their Energy, Land Use, and Greenhouse Gas Emissions Implications: An Overview," *Global Environmental Change*, vol. 42 (January 2017), pp. 153-168.

Notes: Each CO_2 trajectory represents one IAM model run. The legend indicates the model name, followed by the socioeconomic scenario (SSP) and radiative forcing (RCP). RCP 1.9 (denoted as "19" in the legend) is consistent with keeping mean global warming to 1.5°C in 2100. RCP 1.9 refers to the radiative forcing target of 1.9 Wm^{-2} radiative forcing in 2100.

Negative Emissions Technologies

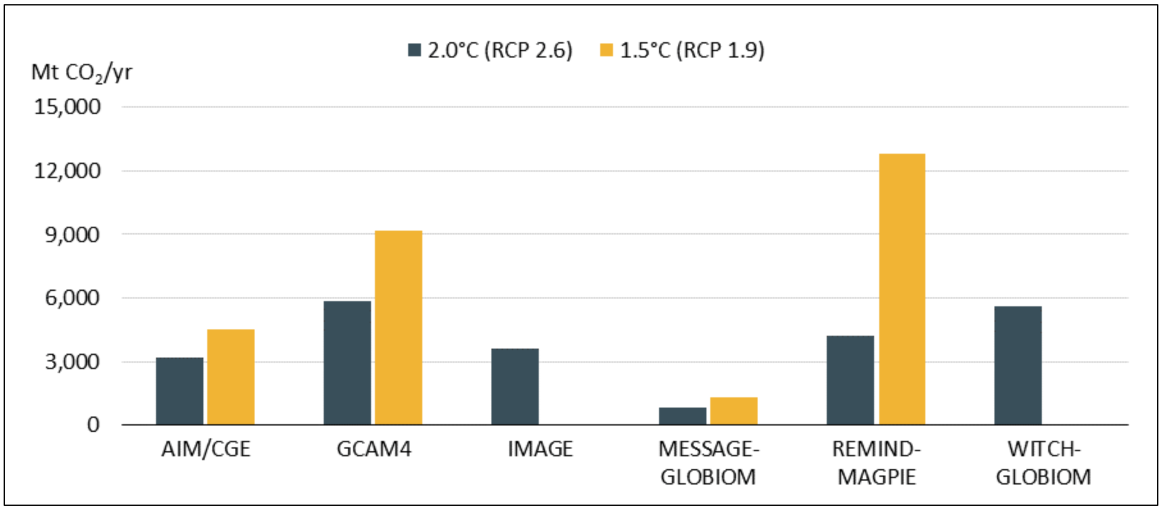
All of the 1.5°C- and 2°C-consistent scenarios illustrated above rely on negative emissions from two main sources, although other technologies could emerge over time: (1) bioenergy with carbon capture and storage (BECCS), where biomass is burned for energy and the resulting CO_2 captured and stored; and (2) terrestrial carbon removal through land use: conservation, restoration, and/or improved land management actions that increase carbon storage and/or avoid GHG emissions in forests, wetlands, grasslands, and agricultural lands (some refer to these as *natural climate solutions*, or NCS).[82]

[82] Bronson W. Griscom et al., "Natural Climate Solutions (Vol 114, Pg 11645, 2017)," *Proceedings of the National Academies of Sciences*, vol. 116, no. 7 (February 12, 2019), p. 2776. See also CRS In Focus IF11693, *Agricultural Soils and Climate Change Mitigation*, by Genevieve K. Croft; and CRS Report R46312, *Forest Carbon Primer*, by Katie Hoover and Anne A. Riddle.

By 2050, models indicate BECCS might remove between 0.8 and 5.9 gigatons (Gt) CO_2 per year across the 2°C-consistent scenarios, and between 1.3 and 12.8 Gt CO_2 per year in the 1.5°C-consistent scenarios (**Figure 7**). The reliance on BECCS to achieve the mitigation targets varies considerably across IAMs, with some models (GCAM and REMIND-MAGPIE) depending much more on the technology. BECCS has two impacts in the models, which is why it is often relied upon: not only does it supply energy to meet energy demands, but it also removes CO_2 from the atmosphere. The 1.5°C- and 2°C-consistent scenarios presented here do not consider all potential carbon removal options, such as direct air capture, enhanced weathering, biochar, soil organic carbon, or ocean fertilization.[83]

Figure 7. Total Annual Global Carbon Capture from BECCS in 2050, by IAM

SSP2 ("middle-of-the-road" socioeconomic scenario)



Source: CRS analysis of data from International Institute for Applied Systems Analysis, "SSP Database (Shared Socioeconomic Pathways) - Version 2.0," at https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=10; Keywan Riahi et al., "The Shared Socioeconomic Pathways and Their Energy, Land Use, and Greenhouse Gas Emissions Implications: An Overview," *Global Environmental Change*, vol. 42 (January 2017), pp. 153-168.

Notes: *BECCS* is bioenergy with carbon capture and storage. RCP 2.6 is consistent with keeping mean global warming to 2°C in 2100, while RCP 1.9 is consistent with keeping mean global warming to 1.5°C in 2100. The database includes only four IAMs that could solve for the RCP 1.9 target for the SSP2 scenario. For IMAGE and WITCH models, no solution could be found. The models include little or no BECCS in the baseline.

Industrial carbon capture and storage (CCS) includes not only BECCS, but also the capture of CO_2 from fossil fuel combustion and other industrial processes (e.g., cement manufacturing).[84] However, BECCS is not possible without the use of CCS facilities. Currently, one industry association estimates that there are 26 operational, commercial CCS facilities worldwide.[85] In total, these

[83] Joeri Rogelj et al., "Scenarios Towards Limiting Global Mean Temperature Increase Below 1.5 °C," *Nature Climate Change*, vol. 8, no. 4 (April 1, 2018), pp. 325-332; Jay Fuhrman et al., "Food–Energy–Water Implications of Negative Emissions Technologies in a +1.5 °C Future," *Nature Climate Change*, vol. 10, no. 10 (October 1, 2020), pp. 920-927.

[84] While BECCS is a negative emissions technology, CCS by itself is not. CCS is a process in which a relatively pure stream of CO_2 from industrial and energy-related sources is separated (captured), conditioned, compressed, and transported to a storage location for long-term isolation from the atmosphere. CCS can be used to capture CO_2 from fossil-fuel burning plants and other industrial facilities (e.g., cement plants), in which case it may be net neutral in CO_2, but not negative. See IPCC, *Global Warming of 1.5°C* (Intergovernmental Panel on Climate Change, 2018); and CRS Report R44902, *Carbon Capture and Sequestration (CCS) in the United States*, by Peter Folger.

[85] Global CCS Institute, "CCS. Vital to Achieve Net-Zero," 2020, at https://www.globalccsinstitute.com/wp-content/

operating facilities have been estimated to sequester 40 $MtCO_2$ per year.[86] BECCS as a technology has not been widely scaled up; globally, there are three commercial BECCS plants in operation (all associated with ethanol production), sequestering 1.39 $MtCO_2$ per year.[87] Given that the 1.5°C and 2°C scenarios described above project a range of carbon capture by BECCS of 800 $MtCO_2$ to 13,000 $MtCO_2$ per year in 2050, this would require global CCS capacity to increase by 20 to more than 300 times in the next 30 years to match these projections.[88]

The models' reliance on BECCS to meet the 1.5°C and 2°C temperature targets correspondingly translates into greater bioenergy crop production compared to the baseline scenarios (**Figure 8**). Without an increase in agricultural productivity or the conversion of other land uses to agriculture, increased bioenergy production could put pressure on food production, prices, or availability.

Besides the issues pertaining to scalability, others have questioned the full carbon cycle impacts of BECCS. A 2018 analysis using a different, more sophisticated vegetation model estimated that carbon removed from the atmosphere through BECCS could be offset by losses due to land-use change from the cultivation of bioenergy crops. According to that analysis, where BECCS involves replacing high-carbon-storing ecosystems with energy crops, forest-based mitigation could be more efficient for atmospheric CO_2 removal than BECCS.[89]

As previously noted, the 1.5°C- and 2°C-consistent scenarios also include varying contributions from terrestrial carbon removal, particularly reforestation and afforestation. Forest area generally increases globally in 2050 in the IAM model results, although some models indicate there could be forest loss in areas of high bio-crop potential.[90] Combined with a general decreased demand for livestock products (due to a shift in diets) in the 1.5°C- and 2°C-consistent scenarios, the models find a decrease in pastureland in 2050.

uploads/2020/12/Global-Status-of-CCS-Report-2020_FINAL_December11.pdf.

[86] Global CCS Institute, "CCS. Vital to Achieve Net-Zero," 2020, at https://www.globalccsinstitute.com/wp-content/uploads/2020/12/Global-Status-of-CCS-Report-2020_FINAL_December11.pdf.

[87] Commercial facilities include those where (1) CO_2 is captured for permanent storage as part of an ongoing commercial operation, (2) storage is undertaken by a third party or by the owner of the capture facility, (3) the economic lifetime is similar to the host facility whose CO_2 they capture, and (4) there is a commercial return while operating and/or meeting a regulatory requirement. Global CCS Institute, "CCS. Vital to Achieve Net-Zero," 2020, at https://www.globalccsinstitute.com/wp-content/uploads/2020/12/Global-Status-of-CCS-Report-2020_FINAL_December11.pdf.

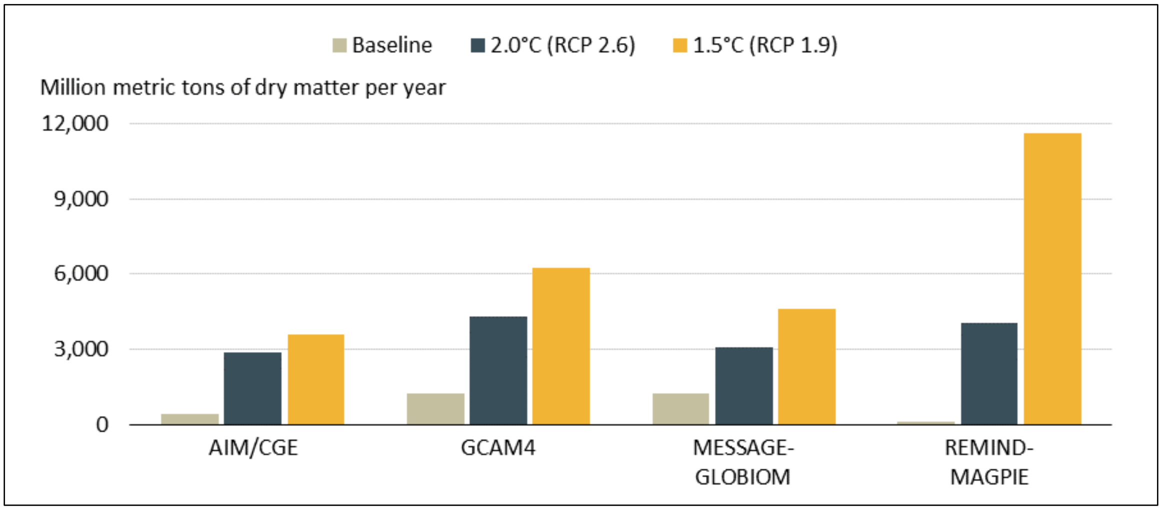
[88] Author's calculations, assuming CCS today sequesters 40 $MtCO_2$ per year.

[89] Anna B. Harper et al., "Land-Use Emissions Play a Critical Role in Land-Based Mitigation for Paris Climate Targets," *Nature Communications*, vol. 9, no. 1 (August 7, 2018), p. 2938.

[90] Anna B. Harper et al., "Land-Use Emissions Play a Critical Role in Land-Based Mitigation for Paris Climate Targets," *Nature Communications*, vol. 9, no. 1 (August 7, 2018), p. 2938.

Figure 8. Bioenergy Crop Production in 2050, by IAM

SSP2 ("middle-of-the-road" socioeconomic scenario)



Source: CRS analysis of data from International Institute for Applied Systems Analysis, "SSP Database (Shared Socioeconomic Pathways) - Version 2.0," at https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=10; Keywan Riahi et al., "The Shared Socioeconomic Pathways and Their Energy, Land Use, and Greenhouse Gas Emissions Implications: An Overview," *Global Environmental Change*, vol. 42 (January 2017), pp. 153-168.

Notes: The models do not assume all bioenergy crops would be used in BECCS (bioenergy with carbon capture and storage. RCP 2.6 is consistent with keeping mean global warming to 2°C in 2100, while RCP 1.9 is consistent with keeping mean global warming to 1.5°C in 2100. The database includes only four IAMs that could solve for the RCP 1.9 target for the SSP2 scenario. For IMAGE and WITCH models, no solution could be found.

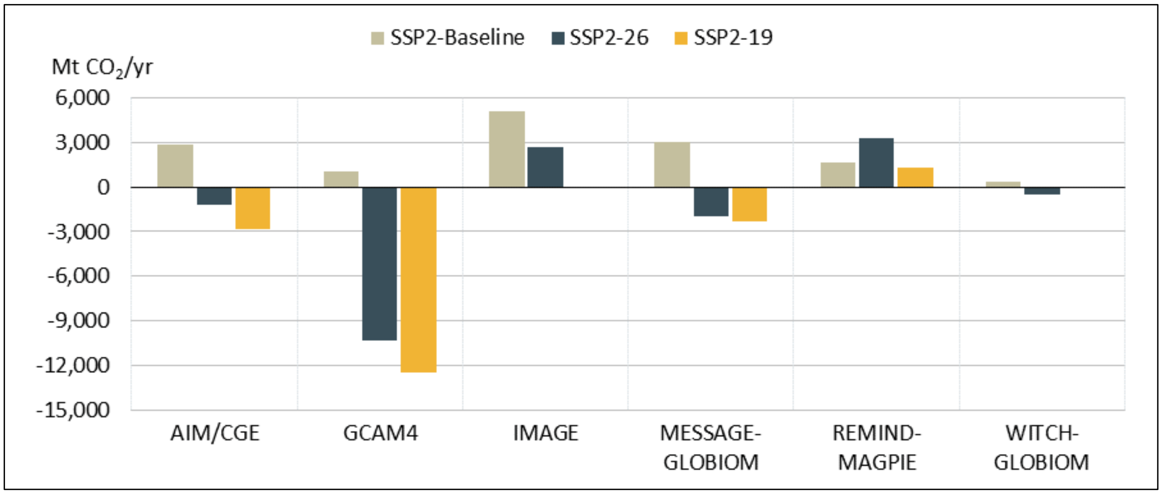
Similarly, to keep likely warming in 2100 to 1.5°C or 2°C, IAMs rely on reductions in land use emissions compared to the baseline (e.g., increases in terrestrial carbon removal, reductions in deforestation), though not all project *absolute* negative land use emissions in 2050. Some IAMs (IMAGE, REMIND) project positive land use emissions in 2050 under the 1.5°C- and 2°C-consistent scenarios. GCAM, in contrast, includes much higher levels of NCS, and projects large overall negative land use emissions (i.e., net sequestration in the land use sector) in 2050. GCAM estimates that land use removes more than 10,000 $MtCO_2$ per year (net) from the atmosphere in the 1.5°C- and 2°C-consistent SSP2 scenarios by 2050 (**Figure 9**). To put this in perspective, one recent review of natural climate solutions estimates that the maximum *additional* potential of NCS—when constrained by food security, fiber security, and biodiversity conservation—is 23,800 $MtCO_2$ per year in 2030.[91] This would be in addition to the 9,500 $MtCO_2$ absorbed annually by terrestrial ecosystems today.[92]

[91] Bronson W. Griscom et al., "Natural Climate Solutions (Vol 114, Pg 11645, 2017)," *Proceedings of the National Academies of Sciences*, vol. 116, no. 7 (February 12, 2019), p. 2776.

[92] Based on 2014 data. Note that net emissions from the land use sector were 1,500 $MtCO_2$ in 2014. Counteracting this sequestering of carbon are positive emissions from forestry and agricultural activities. C. Le Quéré et al., "Global Carbon Budget 2014," *Earth System Science Data*, vol. 7, no. 1 (2015), pp. 47-85.

Figure 9. Global Net Land Use Emissions in 2050, by IAM

SSP2 ("middle-of-the-road" socioeconomic scenario)



Source: CRS analysis of data from International Institute for Applied Systems Analysis, "SSP Database (Shared Socioeconomic Pathways) - Version 2.0," at https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=10; Keywan Riahi et al., "The Shared Socioeconomic Pathways and Their Energy, Land Use, and Greenhouse Gas Emissions Implications: An Overview," *Global Environmental Change*, vol. 42 (January 2017), pp. 153-168.

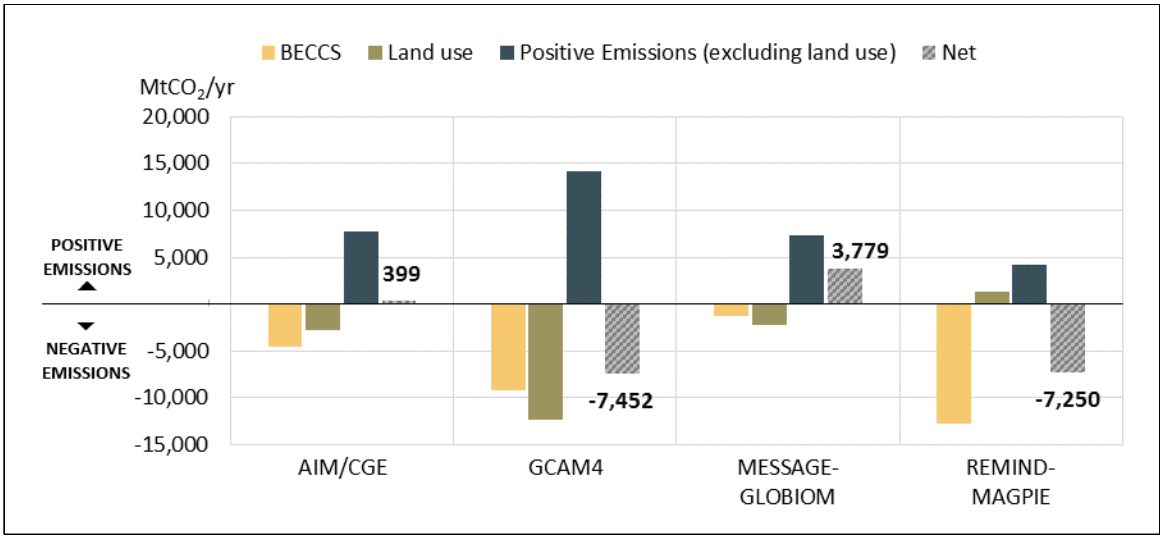
Notes: This figure shows net land use emissions. RCP 2.6 is consistent with keeping mean global warming to 2°C in 2100, while RCP 1.9 is consistent with keeping mean global warming to 1.5°C in 2100. The database includes only four IAMs that could solve for the RCP 1.9 target for the SSP2 scenario. For IMAGE and WITCH models, no solution could be found.

To put the previous analysis in this report in perspective, **Figure 10** shows how negative emissions compare with positive CO_2 emissions (i.e., fossil fuel combustion from energy and transport and industrial processes) in 2050 under the 1.5°C-consistent temperature pathway. Across the IAM model runs, negative emissions represent 49% to 207% of the positive CO_2 emissions from energy, transport, and industrial processes, underscoring how the IAMs rely on negative emissions in order to keep likely warming to 1.5°C or 2°C in 2100.[93] The IAMs vary as to whether BECCS or NCS is the dominant source of negative emissions. One model (REMIND) projects positive land use emissions (green bar in **Figure 10**) in 2050 under the 1.5°C-consistent scenario.

[93] To keep likely warming within 1.5°C/2°C, the models need to select technologies that reduce GHG emissions—for example, by reducing fossil fuel combustion (e.g., in electricity generation or transport). If positive emissions cannot be reduced quickly enough in the models, then those emissions need to be offset with assumed negative emissions technologies that remove CO_2 from the atmosphere (i.e., BECCS) to the degree they are available in the model.

Figure 10. CO_2 Emissions in 2050, by IAM

SSP2 ("middle-of-the-road" socioeconomic scenario), RCP 1.9



Source: CRS analysis of data from International Institute for Applied Systems Analysis, "SSP Database (Shared Socioeconomic Pathways) - Version 2.0," at https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=10; Keywan Riahi et al., "The Shared Socioeconomic Pathways and Their Energy, Land Use, and Greenhouse Gas Emissions Implications: An Overview," *Global Environmental Change*, vol. 42 (January 2017), pp. 153-168.

Notes: Positive emissions include CO_2 emissions from fossil fuel combustion (energy, transport), as well as industrial CO_2 emissions (e.g., cement). *BECCS* is bioenergy with carbon capture and storage. Some models have net negative emissions (GCAM, REMIND), meaning that negative emissions exceed positive emissions. RCP 1.9 is consistent with keeping mean global warming to 1.5°C in 2100. The database includes only four IAMs that could solve for the RCP 1.9 target for the SSP2 scenario. For IMAGE and WITCH models, no solution could be found.

Strengths and Criticisms of IAMs

IAMs can assist researchers and decisionmakers in understanding how complex sets of assumptions on the economic-energy system interact with the biophysical earth system and how various policy actions (e.g., fiscal and regulatory policy) may help achieve objectives. IAMs have been specifically designed to explore technology deployments that meet specified climate or emissions or other constraints (as detailed above with 1.5°C- and 2°C-consistent scenarios) typically in a lowest-cost manner—something that many other models or tools for emissions scenarios cannot easily do. They can also be used to model emissions reductions from a complex suite of policies across sectors and indicate resulting warming.[94] IAMs have utility as structured frameworks to explore various assumptions around costs, performance characteristics, and the availability of different fuels and technologies.[95] In contrast to single-sector models, one strength of IAMs is their ability to explore linkages and tradeoffs among energy use, agriculture, and land use. Like all models, they are most useful not for precise estimates of the future technology or fuel mix under different scenarios, but rather to compare relative results from different policy options.

[94] For the latter, see Nathan E. Hultman et al., "Fusing Subnational with National Climate Action Is Central to Decarbonization: The Case of the United States," *Nature Communications*, vol. 11, no. 1 (October 16, 2020), p. 5255.

[95] Ajay Gambhir et al., "A Review of Criticisms of Integrated Assessment Models and Proposed Approaches to Address These, Through the Lens of BECCS," *Energies*, vol. 12, no. 9 (May 1, 2019), pp. 1-21.

The detailed, process-based IAMs discussed in this report have been criticized on a number of fronts.[96] For example, they have been critiqued for their lack of transparency and “black box” nature; inappropriate input assumptions and outdated data; difficulty in updating the cost of rapidly changing technologies; focus on supply-side technologies; lack of incorporation of innovation processes; lack of incorporation of behavioral processes; limited integration with other policy goals; limited consideration of social, political, economic, and technical barriers and drivers; and coarse spatial and temporal resolution.[97] IAMs vary in the degree to which they are publicly available and the extent of transparency around model assumptions. IAMs tend to be “deterministic”—that is, they often provide one set of results despite uncertainties in input, although one can make multiple runs to explore sensitivities. Most IAMs are not “dynamic” in altering assumptions for a future period based on modeling results from preceding periods. The underlying assumption in IAMs is strong long-term economic growth.[98] Although this is based on historical trends, there is no certainty.

The detailed, process-based IAMs generally do not estimate the economic damages due to the physical impacts of climate change.[99] Thus, there are typically no feedback effects on economic variables, such as GDP growth and labor productivity, from changes in climate. Different IAMs can yield varying results for the same policy—for example, carbon prices—due to the model structure and the available energy technology options. Model intercomparisons, such as the one described in this report, can be instructive as to the outcomes of policy choices.[100]

One of the most prominent criticisms of IAMs has been their reliance on negative emissions technologies, including BECCS. As discussed in the previous section, BECCS would need to scale up by orders of magnitude in these IAM 1.5°C- and 2°C-consistent scenarios. Some have questioned whether BECCS deployment at this scale is technically feasible or realistic,[101] particularly considering the physical or technical limits of biomass production.[102] Furthermore, some contend increased use of BECCS could put additional pressure on biodiversity and ecosystem services, freshwater systems, and biogeochemical cycles.[103] In one 1.5°C scenario study, if BECCS

[96] Ajay Gambhir et al., “A Review of Criticisms of Integrated Assessment Models and Proposed Approaches to Address These, Through the Lens of BECCS,” *Energies*, vol. 12, no. 9 (May 1, 2019), pp. 1-21.

[97] Not every criticism is applicable to every IAM. Ajay Gambhir et al., “A Review of Criticisms of Integrated Assessment Models and Proposed Approaches to Address These, Through the Lens of BECCS,” *ENERGIES*, vol. 12, no. 9 (May 1, 2019), pp. 1-21; Hiroto Shiraki and Masahiro Sugiyama, “Back to the Basic: Toward Improvement of Technoeconomic Representation in Integrated Assessment Models,” *Climatic Change*, vol. 162, no. 1 (September 2020).

[98] Graham Palmer, “A Biophysical Perspective of IPCC Integrated Energy Modelling,” *Energies*, vol. 11, no. 4 (April 2018), at https://doi.org/10.3390/en11040839.

[99] The simpler IAMs (often called *cost-benefit IAMs*) do calculate losses to GDP in each period based on climate damages. The divide between the two model types is not always clear-cut, though, with the full-scale IAM, WITCH, able to undertake cost-benefit analysis through its incorporation of damages from increased temperature changes, and thus the benefits of reducing temperature changes. See Delavane Diaz and Frances Moore, “Quantifying the Economic Risks of Climate Change,” *Nature Climate Change*, vol. 7, no. 11 (November 2017), pp. 774-782.

[100] Jordan T. Wilkerson et al., “Comparison of Integrated Assessment Models: Carbon Price Impacts on US Energy,” *Energy Policy*, vol. 76 (January 2015), pp. 18-31.

[101] Sean Low and Stefan Schäfer, “Is Bio-Energy Carbon Capture and Storage (BECCS) Feasible? The Contested Authority of Integrated Assessment Modeling,” *Energy Research & Social Science*, vol. 60 (2020), p. 101326; Naomi E. Vaughan and Clair Gough, “Expert Assessment Concludes Negative Emissions Scenarios May Not Deliver,” *Environmental Research Letters*, vol. 11, no. 9 (August 2016), p. 095003.

[102] Naomi E. Vaughan and Clair Gough, “Expert Assessment Concludes Negative Emissions Scenarios May Not Deliver,” *Environmental Research Letters*, vol. 11, no. 9 (August 2016), p. 095003.

[103] Vera Heck et al., “Biomass-Based Negative Emissions Difficult to Reconcile with Planetary Boundaries,” *Nature Climate Change*, vol. 8, no. 2 (February 1, 2018), pp. 151-155.

were constrained and not allowed to occur on land converted from natural ecosystems (and assuming the absence of direct air capture technologies), then food prices could increase several times by the end of the 21st century.[104] Lastly, some have argued there is a moral hazard dimension to relying on BECCS and negative emissions technologies more broadly; that is, expected reliance on negative emissions later this century could potentially compromise current efforts to reduce GHG emissions.[105] However, these are not criticisms of IAMs themselves but of particular assumptions used by modelers in structuring their research.

The modeling community has begun to address some of the criticisms of IAMs.[106] For example, there has been some effort to update the technology costs more frequently, to explore different baseline scenarios of fuel use and energy efficiency, to examine tradeoffs with other policy goals (e.g., Sustainable Development Goals), and to incorporate hourly electricity data. Moreover, some recent efforts explore 1.5°C- and 2°C-consistent pathways that are not dependent on BECCS—for example, by assuming lower future energy demand or lifestyle change (e.g., lower-meat diets, lower home heating and cooling demands), additional reduction of non-CO_2 GHGs, and more rapid electrification of energy demand base.[107] The availability of the public SSP-RCP database has made model results more transparent, thus enabling, for example, the comparison in this report.[108]

Some have argued for further transformation or even eliminating the use of IAMs because of the limitations identified above.[109] Models do allow for the exploration of various low carbon emissions scenarios and provide a method to examine the future extraction, transformation, distribution, and use of energy and explore linkages with other sectors in the economy, such as agriculture and land use.

IAMs are simplifications of reality, and all models have limitations. Trying to model the implications of nascent technologies, such as direct air capture, and incorporate feedbacks among policies and behavioral change decades into the future is difficult, and often speculative. The uncertainty in future projections is an inherent limitation of any modeling exercise.

Concluding Observations

Congress may find the projections and comparative results from IAM scenarios useful when considering climate change mitigation proposals. This section highlights selected issues raised by a review of the particular IAM modeling results discussed in this report.

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104 Jay Fuhrman et al., "Food–Energy–Water Implications of Negative Emissions Technologies in a +1.5 °C Future," *Nature Climate Change*, vol. 10, no. 10 (October 1, 2020), pp. 920-927.

105 Kevin Anderson and Glen Peters, "The Trouble with Negative Emissions," *Science*, vol. 354, no. 6309 (2016), pp. 182-183.

106 For a fuller description of criticisms and the IAM community responses, see Ajay Gambhir et al., "A Review of Criticisms of Integrated Assessment Models and Proposed Approaches to Address These, Through the Lens of BECCS," *Energies*, vol. 12, no. 9 (May 1, 2019), pp. 1-21.

107 Detlef P. van Vuuren et al., "Alternative Pathways to the 1.5 °C Target Reduce the Need for Negative Emission Technologies," *Nature Climate Change*, vol. 8, no. 5 (May 1, 2018), pp. 391-397; Arnulf Grubler et al., "A Low Energy Demand Scenario for Meeting the 1.5 °C Target and Sustainable Development Goals Without Negative Emission Technologies," *Nature Energy*, vol. 3, no. 6 (June 1, 2018), pp. 515-527.

108 International Institute for Applied Systems Analysis, "SSP Database (Shared Socioeconomic Pathways) - Version 2.0," at https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=10.

109 Ajay Gambhir et al., "A Review of Criticisms of Integrated Assessment Models and Proposed Approaches to Address These, Through the Lens of BECCS," *Energies*, vol. 12, no. 9 (May 1, 2019), pp. 1-21.

The Role of IAMs in Climate Legislation

Policymakers may look to IAMs and their various GHG emissions policy scenarios to inform legislative decisions regarding climate change objectives and potential mitigation options. IAM results described in this report show model disagreement in some areas (e.g., energy supply mix, the degree of reliance on BECCS). Moreover, two of six IAMs could not find a solution for the 1.5°C-consistent scenario with "middle of the road" socioeconomic assumptions. IAMs vary in their absolute projections (e.g., those pertaining to future primary energy), but they can be particularly instructive where they show agreement. With current technologies and projected future technology costs, the models all generally rely on, inter alia, renewable energy, electrification of end-use energy, and negative emissions technologies to find lowest-cost solutions. Understanding where models disagree and why may also assist consideration of policy options. Other considerations besides costs and technical potential would lead to different modeling results.

Technologies to Reduce GHG Emissions

The global IAM scenarios provide a lowest-cost solution to holding likely global warming to 1.5°C or 2°C in 2100. According to the modeling results presented in this report, renewable energy may need to scale up 3 to 4 times compared to today, and CCS capacity by 20 times to more than 300 times in the next 30 years, to be on track to not exceed those temperature goals in 2100. In 2050, across the model runs, negative emissions may represent half to more than double the positive CO_2 emissions from energy, transport, and industrial processes. The models in the study described here project significant increases in the global demand for electricity by 2050—in some scenarios, electricity demand could reach twice as much as current levels. The modeling results indicate that the energy intensity (energy per unit of GDP) of the world economy in the 1.5°C- or 2°C-consistent scenarios is projected to decline by roughly one-quarter to more than one-third compared to the baseline in 2050. However, the IAMs are used to project the future energy system, but they have limitations in foreseeing what technologies may become available and economically viable in the future. They typically do not consider all potential carbon removal options, and nascent technologies such as direct air capture have only recently been included in scenarios. Additionally, their focus has been more on supply-side technologies than demand-side measures.

If net-zero GHG emissions is a goal, as some Members have stated[110] and introduced legislation to the effect,[111] Congress may seek to consider legislative options, such as incentives to accelerate development and deployment of technologies in such areas as renewable energy, energy efficiency, electrification, nuclear energy, carbon capture and storage, and carbon removal, among others.

[110] "The time for debate and discussion on why and how we must tackle this crisis is over. The science is clear: we must achieve net zero emissions by 2050 in order to ensure a safe and prosperous future for ourselves and our posterity. Now is the time for action and implementation of crucial efforts to save our planet." (Sen. Robert Menendez et al., "Statements on Introduced Bills and Joint Resolution," remarks in the Senate, *Congressional Record*, daily edition, vol. 167 [April 19, 2021], pp. S2013-S2038); "The science is clear: We must achieve net-zero greenhouse gas emissions by 2050 if we're to avoid the most catastrophic consequences of climate change. And we must take decisive action this decade to ensure we're on a path to reaching that target." (Opening statement of Chairman Frank Pallone, in U.S. Congress, House Committee on Energy and Commerce, hearing on "Back in Action: Restoring Federal Climate Leadership," 117th Cong., February 9, 2021).

[111] For example, CLEAN Future Act, H.R. 1512. The bill includes a national, economy-wide goal of net-zero GHG emissions no later 2050.

Appendix A. Details of the IAMs

Table A-1. Comparison of IAMs Referenced in this Report

	AIM/CGE	GCAM	IMAGE	MESSAGE-GLOBIOM	REMIND	WITCH
Organization	National Institute for Environmental Studies (Japan)	Pacific Northwest National Laboratory (USA)	PBL Netherlands Environmental Assessment Agency	International Institute for Applied Systems Analysis (Austria)	Potsdam Institute (Germany)	Fondazione Eni Enrico Mattei (Italy)
Scope	Global	Global	Global	Global	Global	Global
Spatial Resolution (Regions)	17	32 geopolitical regions, 384 land regions, 235 hydrologic basins	26	11	12	17
Economic Structure	General equilibrium	Partial equilibrium	Partial equilibrium	General equilibrium	General equilibrium	General equilibrium
Solution Approach	Simulation	Simulation	Simulation	Optimization	Optimization	Optimization
Base (start) year	2005	1975 (2015 final calibration year)	1970	2000/2010	2005	2005
Time Step	Annual	5 years	1-5 years	10 years	5 years	5 years
Time Horizon	2100	2100	2100	2110	2100	2150

Source: Integrated Assessment Modelling Consortium, "IAMC Wiki," 2020, at https://www.iamcdocumentation.eu/index.php/IAMC_wiki; Joint Global Change Research Institute, "GCAM v5.3 Documentation: GCAM Model Overview," at https://jgcri.github.io/gcam-doc/overview.html.

Appendix B. Summary of SSPs

Table B-1. Assumptions Regarding Economy, Lifestyle, Policies, and Institutions for the Five SSPs of the Intergovernmental Panel on Climate Change

	SSP1: "Sustainability—Taking the Green Road"	**SSP2: "Middle of the Road"**	**SSP3: "Regional Rivalry—A Rocky Road"**	**SSP4: "Inequality—A Road Divided"**	**SSP5: "Fossil-Fueled Development—Taking the Highway"**
Challenges[a]	Low challenges to mitigation and adaptation	Medium challenges to mitigation and adaptation	High challenges to mitigation and adaptation	Low challenges to mitigation, high challenges to adaptation	High challenges to mitigation, low challenges to adaptation
Narrative	"The world shifts gradually, but pervasively, toward a more sustainable path, emphasizing more inclusive development that respects perceived environmental boundaries."	"The world follows a path in which social, economic, and technological trends do not shift markedly from historical patterns. Development and income growth proceeds unevenly, with some countries making relatively good progress while others fall short of expectations."	"A resurgent nationalism, concerns about competitiveness and security, and regional conflicts push countries to increasingly focus on domestic or, at most, regional issues,"	"Highly unequal investments in human capital, combined with increasing disparities in economic opportunity and political power, lead to increasing inequalities and stratification both across and within countries."	"This world places increasing faith in competitive markets, innovation and participatory societies to produce rapid technological progress and development of human capital as the path to sustainable development."
Economy and Lifestyle					
Growth (per capita)	High in low-income countries (LICs), medium-income countries (MICs); medium in high-income countries (HICs)	Medium, uneven	Slow	Low in LICs, medium in other countries	High
Inequality	Reduced across and within countries	Uneven moderate reductions across and within countries	High, especially across countries	High, especially within countries	Strongly reduced, especially across countries
International Trade	Moderate	Moderate	Strongly constrained	Moderate	High, with regional specialization in production
Globalization	Connected markets, regional production	Semi-open globalized economy	Deglobalizing, regional security	Globally connected elites	Strongly globalized, increasingly connected

	SSP1: "Sustainability—Taking the Green Road"	SSP2: "Middle of the Road"	SSP3: "Regional Rivalry—A Rocky Road"	SSP4: "Inequality—A Road Divided"	SSP5: "Fossil-Fueled Development—Taking the Highway"
Consumption and Diet	Low growth in material consumption, low-meat diets, first in HICs	Material-intensive consumption, medium meat consumption	Material-intensive consumption	Elites: high consumption lifestyles; rest: low consumption, low mobility	Materialism, status consumption, tourism, mobility, meat-rich diets
Policies and Institutions					
International Cooperation	Effective	Relatively weak	Weak, uneven	Effective for globally connected economy, not for vulnerable population	Effective in pursuit of development goals, more limited for environmental goals
Environmental Policy	Improved management of local and global issues; tighter regulation of pollutants	Concern for local pollutants but only moderate success in implementation	Low priority for environmental issues	Focus on local environment in MICs, HICs; little attention to vulnerable areas or global issues	Focus on local environment with obvious benefits to well-being, little concern with global problems
Policy Orientation	Toward sustainable development	Weak focus on sustainability	Oriented toward security	Toward the benefit of the political and business elite	Toward development, free markets, human capital
Institutions	Effective at national and international levels	Uneven, modest effectiveness	Weak global institutions/ national governments dominate societal decisionmaking	Effective for political and business elite, not for rest of society	Increasingly effective, oriented toward fostering competitive markets
Technology					
Development	Rapid	Medium, uneven	Slow	Rapid in high-tech economies, slow in others	Rapid
Transfer	Rapid	Slow	Slow	Little transfer within countries to poorer populations	Rapid
Energy Technology Change	Directed away from fossil fuels, toward efficiency and renewables	Some investment in renewables but continued reliance on fossil fuels	Slow technological change, directed toward domestic energy sources	Diversified investments including efficiency and low-carbon sources	Directed toward fossil fuels; alternative sources not actively pursued

	SSP1: "Sustainability—Taking the Green Road"	**SSP2: "Middle of the Road"**	**SSP3: "Regional Rivalry—A Rocky Road"**	**SSP4: "Inequality—A Road Divided"**	**SSP5: "Fossil-Fueled Development—Taking the Highway"**
Carbon Intensity	Low	Medium	High in regions with large domestic fossil fuel resources	Low/medium	High
Energy Intensity	Low	Uneven, higher in low income countries	High	Low/medium	High
Environment and Natural Resources					
Fossil Constraints	Preferences shift away from fossil fuels	No reluctance to use unconventional resources	Unconventional resources for domestic supply	Anticipation of constraints drives up prices with high volatility	None
Environment	Improving conditions over time	Continued degradation	Serious degradation	Highly managed and improved near high/ middle-income living areas, degraded otherwise	Highly engineered approaches, successful management of local issues
Land Use	Strong regulations to avoid environmental tradeoffs	Medium regulations lead to slow decline in the rate of deforestation	Hardly any regulation; continued deforestation due to competition over land and rapid expansion of agriculture	Highly regulated in MICs, HICs; largely unmanaged in LICs leading to tropical deforestation	Medium regulations lead to slow decline in the rate of deforestation
Agriculture	Improvements in agricultural productivity; rapid diffusion of best practices	Medium pace of technological change in agriculture sector; entry barriers to agriculture markets reduced slowly	Low technology development, restricted trade	Agricultural productivity high for large scale industrial farming, low for small-scale farming	Highly managed, resource-intensive; rapid increase in productivity

Source: Reprinted from Brian C. O'Neill et al., "The Roads Ahead: Narratives for Shared Socioeconomic Pathways Describing World Futures in the 21st Century," *Global Environmental Change*, vol. 42 (January 2017), pp. 169-180. Narrative text from Keywan Riahi et al., "The Shared Socioeconomic Pathways and Their Energy, Land Use, and Greenhouse Gas Emissions Implications: An Overview," *Global Environmental Change*, vol. 42 (January 2017), pp. 153-168.

a. "Challenges" refers to whether societal trends in the scenario result in making climate mitigation or adaptation harder or easier, without explicitly considering climate change itself.

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