CellPress OPEN ACCESS

Gold Standard for the Global Goals
1 ton of CO_2 offset

One Earth

Primer

Integrated Climate-Change Assessment Scenarios and Carbon Dioxide Removal

Vanessa J. Schweizer,[1,2,*] Kristie L. Ebi,[3] Detlef P. van Vuuren,[4,5] Henry D. Jacoby,[6] Keywan Riahi,[7] Jessica Strefler,[8] Kiyoshi Takahashi,[9] Bas J. van Ruijven,[7] and John P. Weyant[10]
[1]Department of Knowledge Integration, Faculty of Environment, University of Waterloo, Waterloo, ON, Canada
[2]Balsillie School of International Affairs, Waterloo, ON, Canada
[3]Center for Health and the Global Environment, University of Washington, Seattle, WA, USA
[4]PBL Netherlands Environmental Assessment Agency, Bilthoven, the Netherlands
[5]Copernicus Institute of Sustainable Development, Utrecht University, Utrecht, the Netherlands
[6]Sloan School of Management, Massachusetts Institute of Technology, Cambridge, MA, USA
[7]International Institute for Applied Systems Analysis, Laxenburg, Austria
[8]Potsdam Institute for Climate Impact Research, Member of the Leibniz Association, Potsdam, Germany
[9]Center for Social and Environmental Systems Research, National Institute for Environmental Studies, Tsukuba, Japan
[10]Department of Management Science & Engineering and Director, Energy Modeling Forum, Stanford University, Stanford, CA, USA
*Correspondence: vanessa.schweizer@uwaterloo.ca

https://doi.org/10.1016/j.oneear.2020.08.001

SUMMARY

To halt climate change this century, we must reduce carbon dioxide (CO_2) emissions from human activities to net zero. Any emission sources, such as in the energy or land-use sectors, must be balanced by natural or technological carbon sinks that facilitate CO_2 removal (CDR) from the atmosphere. Projections of demand for large-scale CDR are based on an integrated scenario framework for emission scenarios composed of emission profiles as well as alternative socio-economic development trends and social values consistent with them. The framework, however, was developed years before systematic reviews of CDR entered the literature. This primer provides an overview of the purposes of scenarios in climate-change research and how they are used. It also introduces the integrated scenario framework and why it came about. CDR studies using the scenario framework, as well as its limitations, are discussed. Possible future developments for the scenario framework are highlighted, especially in relation to CDR.

THE GRAND CHALLENGE OF DECARBONIZATION

The Paris Agreement calls on national governments to limit climate change to well below 2.0°C and to pursue efforts toward 1.5°C above pre-industrial temperatures. The biggest contributors to emissions are energy production and land use, including both land conversion and emissions from industrial agriculture. Despite our best efforts to mitigate emissions, throughout this century, human activities in the energy and land-use sectors are likely to retain some emission sources, such as from the transportation sector. Such sources must be balanced by sinks that remove carbon dioxide (CO_2) from the atmosphere. Such sinks can be natural or technology based and are called CO_2 removal (CDR) interventions. Given the need to balance carbon emissions, if emissions overall remain net positive, limiting warming still implies contributions from CDR.

Research summarized in the Intergovernmental Panel on Climate Change Special Report on Global Warming of 1.5°C, or IPCC SR15 (Masson-Delmotte et al., 2018), finds that balancing carbon emissions needs to happen around the middle of the century and even earlier for limiting climate change to 1.5°C with no overshoot; see the top left panel in Figure 1 (Rogelj et al., 2018). CDR could potentially play a key role on such a path to net-zero emissions by mid-century by speeding up the rate at which emissions are reduced. In Figure 1 (top right panel), the thick black line in the schematic summarizes the net amount of CO_2 released to the atmosphere. The thick line reflects the combination of contributions from emission sources above the horizontal axis and sinks removing CO_2 from the atmosphere below the axis. So long as there are gross total CO_2 emission sources (thin black line above the axis), CDR approaches will be needed.

CDR technology in particular has raised concerns of moral hazard, i.e., that governments might delay needed emission reductions now because they could be removed later. Additionally, some approaches to large-scale CDR—such as converting large tracts of land to bio-energy—could possibly threaten food security or efforts to conserve biodiversity. As a result, parties that are otherwise supportive of climate-change mitigation might oppose large-scale CDR. Given these controversies surrounding CDR, its prominent role in the IPCC SR15 was surprising to many. In their reluctance to accept the conclusion that CDR is important to keep climate change well below 2°C, critics have wondered where the IPCC SR15 scenarios come from. This primer provides an overview of the purposes of scenarios in climate-change research, how they are used, and the origins of the IPCC SR15 scenarios. They were derived from components of the integrated scenario framework, which is introduced below. CDR studies based on the integrated scenario framework, as well as its limitations, are discussed. Possible future developments for the

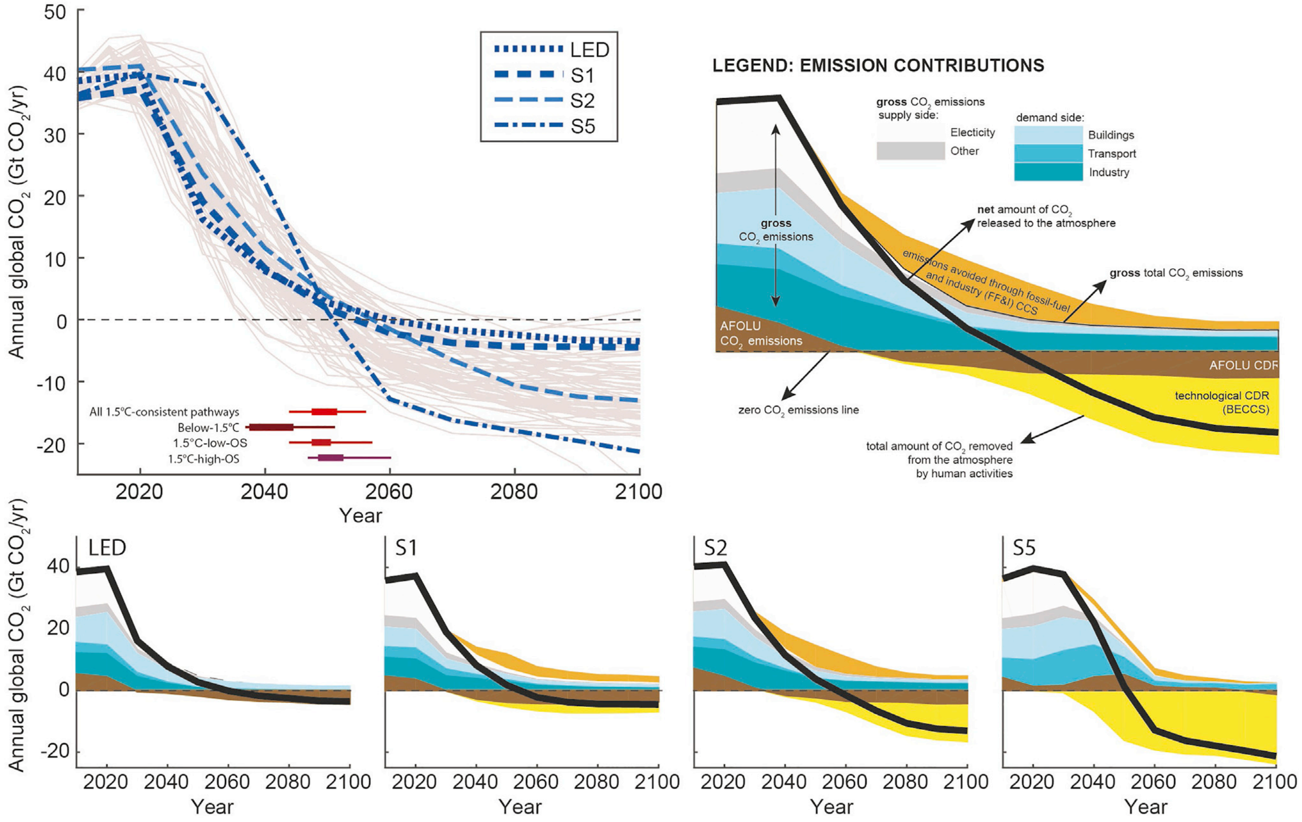

Figure 1. Evolution and Break Down of Global Anthropogenic CO$_2$ Emissions until 2100

The top-left panel shows global net CO$_2$ emissions in Below-1.5°C, 1.5°C-low-overshoot (OS), and 1.5°C-high-OS pathways, with the four illustrative 1.5°C-consistent pathway archetypes of this chapter highlighted. Ranges at the bottom of the top-left panel show the 10th–90th percentile range (thin line) and interquartile range (thick line) of the time that global CO$_2$ emissions reach net zero per pathway class, and for all pathways classes combined. The top-right panel provides a schematic legend explaining all CO$_2$ emissions contributions to global CO$_2$ emissions. The bottom row shows how various CO$_2$ contributions are deployed and used in the four illustrative pathway archetypes (LED, S1, S2, S5, referred to as P1, P2, P3, and P4 in the Summary for Policymakers) used in this chapter (see Section 2.3.1.1). Note that the S5 scenario reports the building and industry sector emissions jointly. Green-blue areas hence show emissions from the transport sector and the joint building and industry demand sector, respectively. This figure and its title and legend are reprinted with permission from Figure 2.5 of the IPCC SR15, published by the World Meteorological Organization.

integrated scenario framework are highlighted especially in relation to CDR.

HISTORY OF SCENARIOS IN CLIMATE-CHANGE RESEARCH

Scenarios have a long history in climate-change research and appeared in the first IPCC Assessment Reports (ARs) approximately 30 years ago. Scenarios employ if-then analysis to explore questions such as, “What *could happen* under a particular set of assumptions?” or “If X is a desirable outcome by year Y, what *should happen* to achieve that goal?” The challenges of climate change are so multi-faceted that research communities representing different disciplines often focus on particular pieces of the climate crisis that align with their expertise. Scenarios aim to integrate these disparate facets of climate-change research to inform related policy (see, e.g., https://climatescenarios.org/primer/).

IPCC ARs reflect the contributions of these research communities according to three working groups (WGs). Physical climate analysis is performed by researchers in IPCC WG I, which focuses on the physical science basis of climate change. Using emission scenarios (where Figure 1 serves as an example) as inputs, climate models project climate-system responses that affect temperature and precipitation patterns regionally and worldwide.

Studies on climate impacts analyze the consequences of climate change on different aspects of society and ecology under different trajectories of socio-economic development. Impact studies are the purview of IPCC WG II, which has a broad remit to assess the risks of climate change from the global to regional scales with models specific to sectors, biomes, or geographic areas. To produce such tailored projections that can be understood as the implications of global change (due to both climatic and non-climatic factors), impact modelers might take as inputs climate-model projections (produced by researchers in WGI) and socio-economic projections (produced by researchers in WGIII).

Emissions scenarios are specified through process-based integrated assessment modeling (IAM) by researchers in IPCC WG III, whose focus is climate-change mitigation. Mitigation refers to methods for reducing greenhouse gas (GHG) emissions, including CDR. IAMs are different kinds of energy-economy

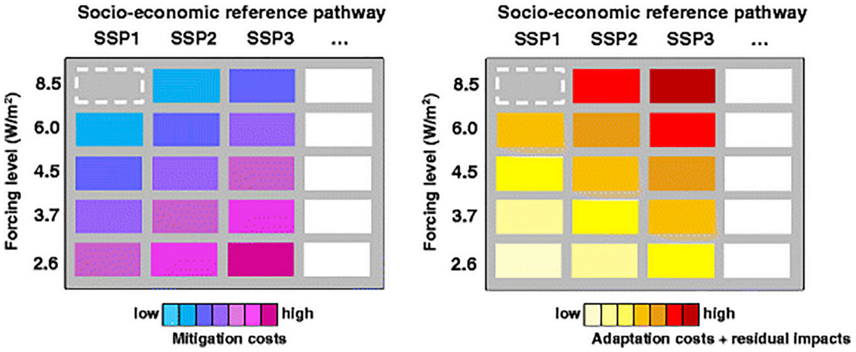

Figure 2. Conceptual Illustrations of How the Integrated Scenario Framework Can Be Used for Assessing the Cost and Benefits of Climate Policy

Different categories of climate-policy costs and residual impacts are expected to vary across the cells of the matrix. The empty cells (dashed lines) illustrate that not all combinations of forcing levels and SSPs are consistent. Colors in the left-hand matrix illustrate how achievement of lower forcing levels imposes a greater mitigation cost for any given SSP but that this cost also requires the SSP to be followed. Colors in the right-hand matrix suggest how the costs of avoiding a certain amount of impact (not specified here) through adaptation, combined with the impact costs that remain, are greater under some SSPs than others and under higher levels of forcing. The 3.7 W/m^2 level has been added to illustrate that levels of radiative forcing other than the original four RCPs can also be explored. Reproduced in accordance with the Creative Commons Attribution 4.0 International License (https://creativecommons.org/licenses/by/4.0/legalcode) from van Vuuren et al. (2014). No changes were made to the figure.

models (e.g., partial-equilibrium energy-land models and computable general equilibrium models of the global economy) that project emissions due to possible future socio-economic developments (see Figure 3), such as population growth, economic development, urbanization, and technology portfolios. IAM can also incorporate socio-economic development pathways as model inputs to explore how different types of policy interventions might affect economic activities, technology portfolios, and commensurate emissions. Development pathways can be either quantitative projections or qualitative descriptions of alternative worlds. In turn, these different bundles of socio-economic priorities produce lower or higher emissions.

Given the division of labor between the three IPCC WGs, there has long been a sequential relationship between emission scenarios, climate projections, and impact studies. Emissions scenarios, which embody particular socio-economic developments resulting in an emission profile, would be generated through IAM first. These were followed by climate projections and then climate-impact projections, as well as bespoke policy analyses for mitigation and/or adaptation. The sequential approach was reasonable for dividing labor across the multidisciplinary climate-change research community. However, the sequential relationship also created difficulties with timing. By the time impact researchers were applying finished climate projections to assess climate-change risks, physical climate researchers had already moved on to develop the next generation of modeling approaches and scenarios to test revised models. The sequential approach created scenario misalignment in the research communities, which complicated the preparation of IPCC ARs. Because there are multiple scenario vintages, concerns emerged about potential inconsistencies among socio-economic, climatic, impact, and policy scenarios. There was also confusion about what scenarios should be used for synthesis.

THE CONTEMPORARY INTEGRATED SCENARIO FRAMEWORK

Emissions scenarios played a key role in coordinating the modeling activities of physical-climate analysts (represented by IPCC WG I) and integrated assessment for cost-optimal mitigation (i.e., WG III). However, the integrated scenario framework departs from the sequential paradigm to make the complex relationship between socio-economic drivers, emission profiles, changes in climate, and impacts from climate change more explicit. Key components of the integrated scenario framework are representative concentration pathways (RCPs), which are emission profiles (used by researchers in IPCC WG I as harmonized *inputs* for climate modeling), and shared socio-economic pathways (SSPs), which specify different futures with contrasting socio-economic conditions that make mitigation, adaptation, or both more (or less) challenging while setting aside changes in climate. IAM can use SSPs to investigate alternative emission profiles that are the *result* of alternative socio-economic development patterns as well as climate-policy goals.

The integrated scenario framework enables research questions such as, "If we overshoot the goals of the Paris Agreement but succeed in alleviating existing socio-economic vulnerabilities, how well might we (and natural systems for that matter) manage climate-change risk?" Acknowledging their dual role across research communities, the integrated scenario framework presents emission scenarios in two dimensions (Figure 2). For the physical climate science research community, RCPs serve as "basic" alternative emission profiles that should be considered abstracted from socio-economic drivers. Although RCPs have been vetted as plausible through at least one IAM simulation, they are not part of a set of scenarios with overarching internal logic. Separately, "basic" socio-economic scenarios (i.e., SSPs) were developed with their own framework providing overarching internal logic (i.e., the SSP framework), and they describe (and quantify) portfolios of socio-economic developments that replicate the RCP emission profiles (see van Vuuren et al., 2014 for a conceptual introduction and Riahi et al., 2017 for results). This means that climate-impact studies and policy analyses—which take both projected changes in climate (the output of climate modeling) and alternative socio-economic projections (the output of IAM) as input data—reflect particular RCP-SSP (or SSP-RCP) pairings.

A key benefit of the integrated scenario framework is that scenarios are now better understood as reflecting outcomes of particular selections from a menu of policy options: the climatic effects of possible mitigation targets and differences in timing, which are explored with RCPs; meanwhile, SSPs qualitatively describe and quantitatively project different socio-economic

Table 1. Representative Types of Approaches to CDR

Nature-Based Approaches	
Afforestation and reforestation	forest cover is expanded via land management or conversion
Soil carbon sequestration	carbon storage in agricultural soils is enhanced through changes in the management of forests, grassland, or agricultural practices
Agroforestry	trees are incorporated into agricultural systems
Blue carbon	land-use and management practices store carbon in living plants or sediments in ecosystems such as the ocean, mangroves, tidal marshes, seagrass beds, and other tidal or salt-water wetlands
Carbon mineralization and accelerated weathering	CO_2 ambient in air is mineralized on exposed rock or injected into appropriate rocks where it mineralizes in pores
Technology-Based Approaches	
BECCS	bio-energy, or plant biomass, is used for producing liquid fuels (e.g., for the transportation sector), electricity, and heat combined with CCS
Direct air capture	chemical processes capture CO_2 from ambient air and concentrate it so that it can be stored, such as in a storage reservoir
CCU	CO_2 is used in feedstocks for materials in the industrial sector

Given that scientific assessments of CDR are ongoing, this list is not comprehensive. Approaches have been grouped into nature-based and technology-based categories. Abbreviations are as follows: BECCS, bio-energy and carbon capture and sequestration; CCS, carbon capture and sequestration; CCU, carbon capture and utilization; CDR, carbon dioxide removal.

conditions, which can influence whether different mitigation and/or adaptation policy implementations are challenging (or straightforward). The SSP framework refers to the latter as socio-economic challenges to mitigation or adaptation. Impacts are determined by the simultaneous combination of climatic and socio-economic factors (e.g., Raymond et al., 2020).

The integrated scenario framework also aims to flexibly guide the larger enterprise of multidisciplinary and cross-scale scenario analysis needed for climate-change research rather than to merely refresh particular versions of emission scenarios that are being applied. It is important to acknowledge that all scenario studies are illustrative examples of what could happen in the future; what is more useful is scientific assessment incorporating a variety of modeling and analytical approaches to glean what findings are universal versus sensitive to context or active areas of research. First-generation RCPs and SSPs were careful to present themselves as "basic" versions that could be modified or elaborated upon as needed to ensure that downstream scenario studies would be fit for purpose (see O'Neill et al., 2014). In this regard, the integrated scenario framework aims to support the creativity of research teams to make their science policy relevant while retaining as touchstones canonical marker projections for RCPs (https://tntcat.iiasa.ac.at/RcpDb/), SSPs (https://tntcat.iiasa.ac.at/SspDb/), and SSP narratives (O'Neill et al., 2017). Naturally, this orientation toward flexibility applies also to the integrated scenario framework itself. Framework components will evolve in light of new findings, such as the socio-economic change already observed in rapidly developing economies or as might be underway as a result of the coronavirus disease 2019 (COVID-19) pandemic.

Key findings based on the integrated scenario framework have confirmed the importance of making concrete progress this decade on policy commitments to decrease emissions that are internationally coordinated (e.g., Riahi et al., 2017; IPCC SR15). However, the integrated scenario framework was developed years before systematic reviews and scientific assessments of large-scale CDR entered the literature (Minx et al., 2018; NAS, 2019). The ways in which approaches to CDR are reflected (or not) through the integrated scenario framework provide a case study of some of its current limitations.

CDR AND INTEGRATED SCENARIOS

Scientific assessments of CDR are ongoing and might not yet be as comprehensive as desired. Table 1 provides a list of key approaches that could be investigated in the integrated scenario framework, and these are grouped as nature or technology based. Importantly, some technologies, such as soil carbon sequestration, are inexpensive and have beneficial environmental effects. Some technologies can also have multiple uses (e.g., microalgae as a food or feed source).

The integrated scenario framework serves the multi-disciplinary climate-change research communities in different ways, and research communities concern themselves with different questions about CDR. As discussed previously, RCPs for physical climate modeling are emission trajectories vetted by an IAM simulation yet abstracted from particular socio-economic conditions. Thus, the salient features of RCPs are the amount of radiative forcing projected by the year 2100 as well as whether emissions peak and when. From a physical science perspective, CDR is interesting as interventions that could bend CO_2 emissions downward or perturb regional (and global) biogeochemistry (i.e., CO_2 fluxes) and biophysics (albedo and evapotranspiration). Such features reflected in the RCPs will affect changes in climate. From a socio-economic perspective, interesting questions surrounding CDR include demand in light of larger socio-economic trends or climate-policy targets, what CDR interventions become available at scale and when, and where they are deployed. For example, if CDR is land based, IAM with SSPs can explore what limits there might be to land available for other uses.

Findings from the SSPs

The exploratory and explanatory power of the SSP framework has been fairly successful for showing potential opportunity costs in the use of land for CDR, such as for bio-energy versus forest. A key message of the IPCC SR15 is that although CDR can be key for accelerating emission reductions in time to keep climate change to 1.5°C, larger socio-economic trends matter a great deal for how much and what type of CDR might be demanded.

When interpreting CDR projections, it's important to remember that a scenario is a particular bundle of assumptions. The SSP

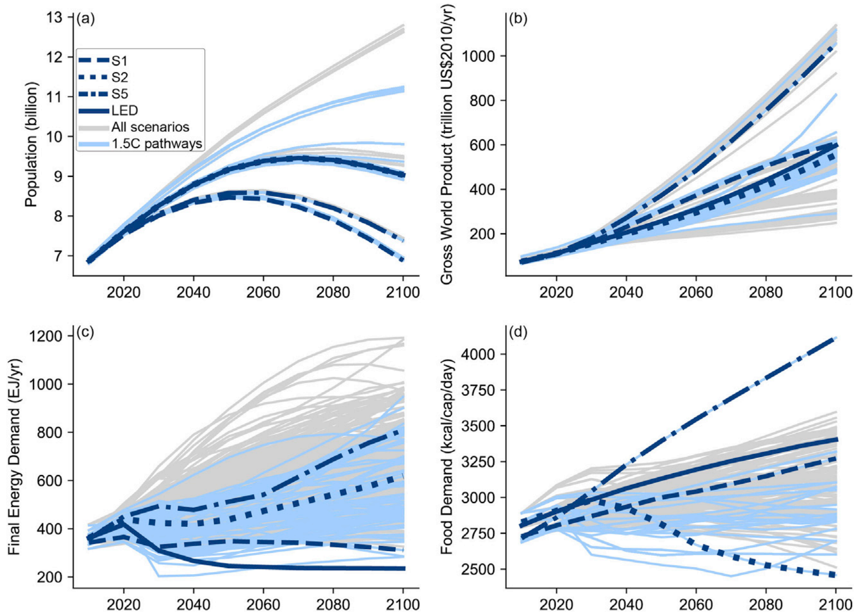

Figure 3. Range of Assumptions about Socio-economic Drivers and Projections for Energy and Food Demand in the Pathways Available to This Assessment

1.5°C-consistent pathways are blue, other pathways grey. Trajectories for the illustrative 1.5°C-consistent archetypes used in this Chapter (LED, S1, S2, S5; referred to as P1, P2, P3, and P4 in the Summary for Policymakers.) are highlighted. S1 is a sustainability oriented scenario, S2 is a middle-of-the-road scenario, and S5 is a fossil-fuel intensive and high energy demand scenario. LED is a scenario with particularly low energy demand. Population assumptions in S2 and LED are identical. Panels show (a) world population, (b) gross world product in purchasing power parity values, (c) final energy demand, and (d) food demand. This figure and its title and legend are reprinted with permission from Figure 2.4 of the IPCC SR15, published by the World Meteorological Organization.

narratives (O'Neill et al., 2017) characterize alternative underlying value commitments that set priorities for global socio-economic development. In turn, these development patterns influence what mitigation options emerge as acceptable. For example, scenario S5 in Figure 3 is based on SSP5, characterized by "fossil-fueled development," which describes a future where a fossil-fueled and energy-intensive lifestyle drives the global economy to grow faster than it has historically (note the high trajectory for gross world product in Figure 3B). Global values toward consumption in the SSP5 world are similar to those today, e.g., a preference for meat-based diets and convenient mobility, such as the prolific use of personal vehicles and aviation. However, the successes in economic growth and the widespread provision of decent work simultaneously decrease global population because increased wealth increases demand for skilled labor, encouraging countries to train all of their citizens (including girls) and leading to small family sizes (Figure 3A). However, even with a small global population, these social values correspond to projections for high demand for calorie-rich diets (Figure 3D) and the highest energy-demand trajectory of the illustrative scenarios (Figure 3C). Such a world has high global emissions overall, as shown in Figure 1 (bottom row). Although all 1.5°C-compatible pathways must peak annual global CO_2 emissions at approximately 40 Gt CO_2 per year, the S5 scenario has more difficulty with significantly decreasing its emission sources until about 2050 (note also its larger share of emissions in transportation than in other scenarios). Scenario S5 is thus more reliant on CDR to achieve 1.5°C and begins scaling up bio-energy and carbon capture and sequestration (BECCS) in 2030. Such strategies are consistent with the technologically optimistic social values of SSP5, where technological applications are preferred to meet sustainability goals.

In contrast, scenario S1 is based on SSP1, characterized by "sustainability," which describes a future where sustainable development becomes the norm. The global economy for S1 grows at a pace similar to historical trends (Figure 3B). The global population is also low for reasons similar to those in S5; however, added to this is global concern with population size, so small family sizes are preferred (Figure 3A). Global values toward consumption in the SSP1 world are different from those today, e.g., plant-based diets are preferred. Additionally, active mobility (e.g., bicycles) or mass transit (trains versus personal vehicles and planes) are preferred. These social values translate to important differences for food and energy demand between S1 and S5. Even though S1 and S5 have similarly sized populations, caloric demand in S1 is about 25% lower than that in S5 as a result of dietary preferences (Figure 3D). Similarly, the S1 world is committed to energy conservation and efficiency and has low energy demand (Figure 3C). Such a world has lower global emissions overall, as shown in Figure 1, and moves 20 years earlier than S5 to significantly decrease emission sources in 2030. The S1 world also makes different choices for CDR. The social values of SSP1 are biophilic in that the preference is to meet sustainability goals through nature-based solutions first. Hence, the largest share of its CDR comes from agriculture, forestry, and land use rather than technologies.

The comparison of S5 and S1 shows how socio-economic trends and social values interplay to influence the overall amount of emissions and their sources and how challenging it might be to offset emission sources with CDR. It also shows how social values influence options for CDR. The low-energy-demand (LED) scenario investigated whether 1.5°C could be achieved without technological CDR (Figure 1). The answer is yes, but this outcome is enabled through an ambitious global commitment to significantly decreasing energy consumption this decade. Similarly, Edmonds et al. (2013) found that BECCS CDR is not necessary for bringing radiative forcing down to 2.6 W/m^2 by the year 2100; however, such findings were contingent upon the commitment of all nations worldwide to emission reductions no later than 2070 (and that major emitters in industrialized countries and China would participate first by the year 2030) and that all participating countries would make monumental efforts to mitigate emissions (as reflected by carbon prices in excess of \$500/tCO_2 by 2040 for scenarios not deploying bio-energy). Such findings demonstrate that if reliance on any large-scale technology-based CDR is to be avoided, ambitious mitigation actions should be implemented quickly.

Limitations of the Integrated Scenario Framework

Given the large suite of options that might be available for CDR, it is important to acknowledge the limitations of how CDR is represented in IAM. The main approaches considered have been land-based CDR, such as afforestation and reforestation, and BECCS; mostly missing are explicit assumptions regarding how marine-based CDR might be managed. Research with SSPs has also focused on the technical feasibility of CDR to reach climate targets by 2100. Less attention has been paid to institutional factors that might delay CDR availability at scale, such as the maturity of carbon markets or the ability to secure financing.

Despite the success of SSPs to show that socio-economic trends and priorities matter for selecting strategies that could achieve climate-policy goals, research on the potential land-use impacts of CDR reveals an important difficulty for the departure of the integrated scenario framework from ‘‘emission scenarios’’ to emission profiles (RCPs) paired with socio-economic scenarios (SSPs). In the case of impact research on land-based CDR, the difficulty is that some variables in the integrated scenario framework act as *independent* variables in one research community (for physical climate analysis, the land-use assumptions embedded within RCPs) but as *dependent* variables in another research community (for IAM, deployment of CDR is subject to different socio-economic trends and aims to achieve particular targets for GHG concentrations).

The potential challenge for the integrated scenario framework of having land-use assumptions ‘‘baked in’’ to RCPs without overarching socio-economic scenario logic was acknowledged early on but flagged as an issue requiring further research (van Vuuren et al., 2011). This could be because the IAM community is familiar with how different combinations of socio-economic trends can yield similar outcomes, such as for an emission profile. However, for the impact modeler who might wish to analyze the impacts on food production of climate change at the forcing level of RCP3.4 and land-based CDR under SSP5, it could be problematic that the RCP presumes a particular land-use pattern while the marker SSP5 scenario also has a land-use pattern that is not identical. Currently, such gaps could be handled through ‘‘RCP replication,’’ where an analyst compares characteristics of emission profiles resulting from their study to the original RCP; however, this is an extra step that might not be completed. The need for such double checking currently complicates impact assessment for CDR, and a proper resolution of this limitation requires further research. Importantly, the integrated scenario framework was developed to promote coordination between the research communities represented by the three IPCC WGs and not to assess the efficacy of any particular technology or policy on achieving any particular set of climate-policy objectives. CDR, however, could be an example of particular interventions where it would be useful to develop harmonized global change scenarios for the purpose of impact and risk assessment.

IMPROVING THE INTEGRATED SCENARIO FRAMEWORK

The integrated scenario framework should continue to be refined to include CDR to further illuminate ‘‘not implausible’’ transition pathways from today’s GHG emission trajectories to more sustainable pathways. To improve the capacity of analysts to simulate the various options for CDR, several of which involve impacts on land use and land-use change, it might be desirable to construct a new set of marker scenarios that somehow disentangle the land-use assumptions that are built into the current set of RCPs and SSPs. Deciding on the revised design would be a research task, and discussions within the scientific community are ongoing to specify Community Climate Intervention Strategies (which ideally would also be appropriate for researching the impacts of geoengineering or solar-radiation management). In order to construct scenarios that would serve a wide range of analyses, we should identify areas where analysis frameworks will need to incorporate a representation of the carbon cycle that is more complete than many now incorporate, including the IPCC SR15.

Importantly, CDR is explored as an option to offset emission sources that are difficult to reduce further. However, the extent to which emission sources can be reduced also remains uncertain and depends upon success in developing and adopting a range of new energy-efficient technologies (e.g., enabling technologies for grid integration and advanced energy-efficiency options). Research developments in these fields are highly relevant to research on CDR.

To improve assessments of CDR, a more complete integration of top-down global market-share projections with more systematic local to regional multi-metric sustainability projections is required. Without further integration, top-down models might project large-scale CDR increases that would be unsustainable at the local scale and thus internally inconsistent when the scenarios are examined across scales. Moreover, this reality highlights the need to assess climate mitigation and impacts, adaptation, and vulnerability at a scale where sustainability metrics can be examined. The recent National Academies of Sciences, Engineering, and Medicine (NAS) report (NAS, 2019) aims for a systematic and comprehensive set of physical sustainability impacts to which the socio-economic dimensions of the SSPs and policy analyses could be synchronized. Updated global modeling studies have already factored in more granular sustainability criteria into scenarios including BECCS (see Muratori et al., 2020) and natural carbon sinks, as discussed in the 2019 IPCC Special Report on Climate Change and Land. These studies show less BECCS potential than discussed in the IPCC AR5, but the potential is still substantial, and the decrease is partially offset by increases in projected natural-sink potential.

Given that different approaches to large-scale CDR are at various stages of maturity, top-down assessments should incorporate recent projections of future costs and performance of both CDR and all competing technologies. Analytic projections of such metrics should be augmented by—and compared with—expert elicitations (e.g., Verdolini et al., 2018). These projections should include ranges and probabilities over possible cost and performance parameters that can be used in constructing future scenarios as well. Meanwhile, bottom-up sustainability assessments will require comprehensive full life-cycle data on costs; air and water environmental impacts by region, gender, and race; and estimates of leakage and degree of storage permanence.

Such scenarios could be used to frame the role of CDR in a risk assessment with uncertainty about when and how much CDR will be available and acceptable in light of other priorities, such as the Sustainable Development Goals (SDGs). Some forms of CDR might be fine from a climate perspective but might not be pursued if governments also aim to achieve other SDGs, such as preventing biodiversity loss or hunger. This means that analysts should consider how the SSP narratives articulate SSP-specific socio-economic constraints that will influence which CDR portfolios emerge as consistent. Different approaches to CDR could imply vastly different trade-offs for other non-climate objectives, including SDGs and the sustainability of climate policies. As was shown in the comparison of the S1 and S5 scenarios from the IPCC SR15, some CDR approaches will be less compatible with some of the social values articulated in different SSP narratives. Existing SSP narratives, however, are largely silent on biodiversity SDGs, namely Life below Water (SDG 14) and Life on Land (SDG 15). Whenever the narratives are updated, social value orientations toward these additional sectors—which relate to ocean acidification as well as marine- or land-based CDR—should be represented explicitly.

RECOMMENDED READING

Edmonds, J., Luckow, P., Calvin, K., Wise, M., Dooley, J., Kyle, P., Kim, S.H., Patel, P., and Clarke, L. (2013). Can radiative forcing be limited to 2.6 Wm^{-2} without negative emissions from bioenergy and CO_2 capture and storage? Clim. Change *118*, 29–43.

V. Masson-Delmotte, P. Zhai, H.O. Pörtner, D. Roberts, J. Skea, and P.R. Shukla, et al., eds. (2018). Global Warming of 1.5°C. An IPCC Special Report on the Impacts of Global Warming of 1.5°C above Pre-industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty (Intergovernmental Panel on Climate Change). https://www.ipcc.ch/sr15/.

Minx, J.C., Lamb, W.F., Callaghan, M.W., Fuss, S., Hilaire, J., Creutzig, F., Amann, T., Beringer, T., Garcia, W. de O., Hartmann, J., et al. (2018). Negative emissions—part 1: research landscape and synthesis. Environ. Res. Lett. *13*, 063001.

Muratori, M., Bauer, N., Rose, S.K., Wise, M., Diaoglu, V., Cui, Y., Kato, E., Gidden, M., Strefler, J., Fujimori, S., et al. (2020). EMF-33 insights on bioenergy with carbon capture and storage (BECCS). Clim. Change. https://doi.org/10.1007/s10584-020-02784-5.

National Academies of Sciences, Engineering, and Medicine (2019). Negative Emissions Technologies and Reliable Sequestration: A Research Agenda (The National Academies Press). https://doi.org/10.17226/25259.

O'Neill, B.C., Kriegler, E., Ebi, K.L., Kemp-Benedict, E., Riahi, K., Rothman, D.S., van Ruijven, B.J., van Vuuren, D.P., Birkmann, J., Kok, K., et al. (2017). The roads ahead: narratives for shared socioeconomic pathways describing world futures in the 21st century. Glob. Environ. Change *42*, 169–180.

O'Neill, B.C., Kriegler, E., Riahi, K., Ebi, K.L., Hallegatte, S., Carter, T.R., Mathur, R., and van Vuuren, D.P. (2014). A new scenario framework for climate change research: the concept of shared socioeconomic pathways. Clim. Change *122*, 387–400.

Raymond, C., Horton, R.M., Zscheischler, J., Martius, O., AghaKouchak, A., Balch, J., Bowen, S.G., Camargo, S.J., Hess, J., Kornhuber, K., et al. (2020). Understanding and managing connected extreme events. Nat. Clim. Chang. *10*, 611–621.

Riahi, K., van Vuuren, D.P., Kriegler, E., Edmonds, J., O'Neill, B.C., Fujimori, S., Bauer, N., Calvin, K., Dellink, R., Fricko, O., et al. (2017). The shared socioeconomic pathways and their energy, land use, and greenhouse gas emissions implications: an overview. Glob. Environ. Change *42*, 153–168.

Rogelj, J., Shindell, D., Jiang, K., Fifita, S., Forster, P., Ginzburg, V., Handa, C., Kheshgi, H., Kobayashi, S., Kriegler, E., et al. (2018). Mitigation pathways compatible with 1.5°C in the context of sustainable development. In Global Warming of 1.5°C. An IPCC Special Report on the Impacts of Global Warming of 1.5°C above Pre-industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty, V. Masson-Delmotte, P. Zhai, H.O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, and R. Pidcock, et al., eds. (Intergovernmental Panel on Climate Change). https://www.ipcc.ch/sr15/chapter/chapter-2/.

van Vuuren, D.P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., Hurtt, G.C., Kram, T., Krey, V., Lamarque, J.-F., et al. (2011). The representative concentration pathways: an overview. Clim. Change *109*, 5–31.

van Vuuren, D.P., Kriegler, E., O'Neill, B.C., Ebi, K.L., Riahi, K., Carter, T.R., Edmonds, J., Hallegatte, S., Kram, T., Mathur, R., and Winkler, H. (2014). A new scenario framework for climate change research: scenario matrix architecture. Clim. Change *122*, 373–386.

Verdolini, E., Anadón, L.D., Baker, E., Bosetti, V., and Aleluia Reis, L. (2018). Future prospects for energy technologies: insights from expert elicitations. Rev. Environ. Econ. Policy *12*, 133–153.