

Achieving global climate goals by 2050

Pathways to a 1.5° C future

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Cover photo: Aerial view of a rural road in the U.K. countryside. (iStock)

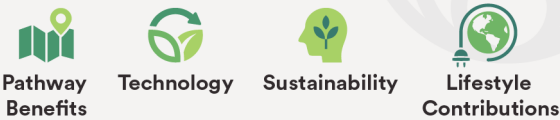
Executive summary

This is the second edition of the ClimateWorks Global Intelligence report, “Achieving global climate goals by 2050: Actionable opportunities for this decade.” The findings highlighted in this report are intended to serve as a resource for climate funders and others interested in climate change mitigation to identify priorities for emissions reductions. The report outlines many intervention areas within electricity, fuel supply, transport, buildings, industry, land use, agriculture, and technological carbon dioxide removal and across 10 global geographies, with a focus on achieving net-zero CO₂ emissions by 2050. These priorities are designed through a scenario exercise with a modeling tool that captures a nuanced story about the linkages and trade-offs inherent in climate change mitigation strategies.

The modeling results illustrate pathways toward achieving the emissions reductions needed to achieve a 1.5° C compatible pathway with limited temperature overshoot (a temporary rise in temperature above the targeted rise of 1.5° C at any time between now and 2100) and are intended to serve as a guide to indicate the scale or impact of possible reductions. Ultimately, intervention strategies must be designed to realize these emissions reductions and to carefully evaluate other considerations such as effects on communities, human health, and social and economic factors — and additional work and research is required to examine their intersections. These strategies will help mobilize the scale of change needed to achieve challenging emissions reductions.

In this year’s report, we introduce an Ensemble of scenarios that takes into consideration a balance of approaches while achieving net-zero carbon dioxide emissions by 2050. These include factors related to technology diffusion, the use of efficiency and productivity measures, the potential for changes in human behavior and lifestyle, the use of zero-emissions alternate energy sources, and how all these factors interact with land systems. The Ensemble scenarios focus on key groupings of modeling parameters, which allows an informed discussion on a wider range of possible outcomes across technologies, sectors, and geographies (see Figure 2 for detail). Within the Ensemble, we identify a Central, anchoring scenario from which to compare these parameters (see Figure 1). This Central scenario was informed by interactions with philanthropic organizations, which revealed the need to assess pathway co-benefits, the role of technology, sustainability, and lifestyle contributions. This new framework of comparing the Ensemble and Central scenarios reveals additional nuance, linkages, and trade-offs inherent to any climate change mitigation strategy.

FIGURE 1: KEY NARRATIVE THEMES AND MODELING PARAMETERS FOR THE CENTRAL SCENARIO



For more on narrative themes, see Table 1, page 10.

	Carbon Capture and Sequestration (CCS)	LOW
	Direct Air Capture (DAC)	LOW
	Nuclear	LOW
	Renewable Energy	HIGH
	Bioenergy	LOW
	Transport Electrification	HIGH
	Behavioral	MED
	Natural CDR	LOW

For more on modeling parameters, see Figure 6, page 11. Throughout the report, we test these parameters within the Ensemble scenarios and compare them with these default low-med-high settings as outlined in the Central scenario. See the Technical Summary for more details on parameter definitions.

Near-term action is necessary to achieve an ambitious pathway. By 2030 under the Central scenario, we envision reductions of annual emissions by roughly 50% relative to current levels, setting the stage for further reductions of more than 90% by 2050. Such steep reductions minimize temperature overshoot, thereby reducing the potential to hit tipping points. In comparison with a Reference scenario, the Central scenario achieves a reduction in annual emissions of around 70 GtCO₂e by 2050, distributed across sectors and geographies (Figure 3). This 70 Gt represents a spectrum of opportunities available and is used in this report as a baseline point of comparison for the wider Ensemble of scenarios.

The types of interventions discussed in the report cover the energy and land-use sectors within various geographies from 2030 to 2050. These sectors include:

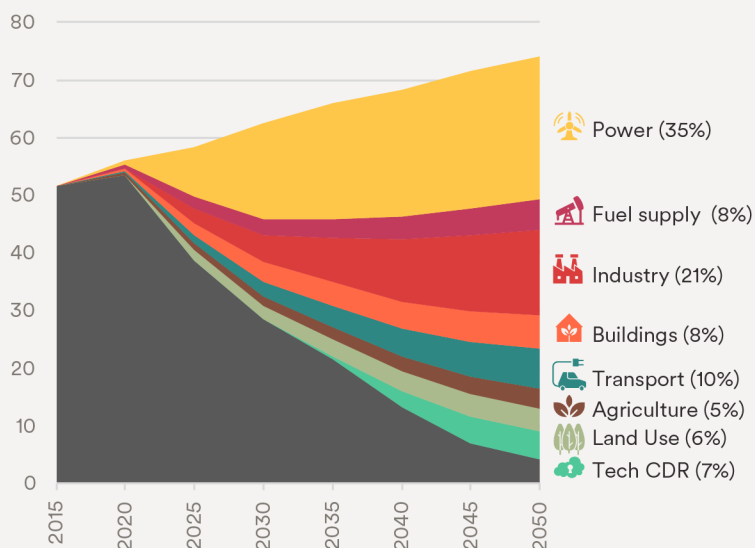
- **Electricity:** Completely phasing out unabated fossil-fuel generation by 2040 while rapidly scaling renewables and other zero-emissions generating technologies and deploying storage and improvement mechanisms that ensure reliability and resiliency of the grid
- **Fuel supply:** Curbing emissions associated with the processing and refining of fuels through a combination of increased productivity and efficiency measures, the use of waste and alternate zero-carbon fuels for heat and feedstocks, and the deployment of carbon capture and sequestration (CCS)
- **Industry:** Regulating disclosures and reporting for corporate emissions while creating incentives for productivity/efficiency, fuel switching including electrification, and the use of zero-carbon alternate fuels for high-heat applications within industry
- **Buildings:** Lowering costs and administrative barriers while providing incentives for comprehensive upgrades to equipment and appliances, retrofits of building stocks, and the design and construction of more climate-friendly and climate-resilient buildings
- **Transport:** Implementing regulatory frameworks that establish timelines to end the sale of internal combustion engines and financial incentives that aim to scale investments in alternative fuel development and deployment, vehicle and fleet purchasing, and the build-out of necessary infrastructure
- **Forests:** Aligning incentives and strengthening the implementation of existing policies so that the forest and land use sectors can shift from being major emitters to net carbon sinks while also benefiting local communities. This includes bridging knowledge gaps regarding the potential impacts and financial risks associated with the loss and degradation of ecosystems
- **Agriculture:** Changing food production methods and promoting demand-side shifts in diet (especially moving away from emissions-intensive protein sources) while also looking more broadly at system approaches to distribution, processing, and minimizing food waste by both producers and consumers
- **Carbon dioxide removal (CDR):** Promoting research and development to help implement a wider portfolio of natural and technological CDR options and to understand their potential contribution to mitigation efforts and overall impacts on people and planet

Such interventions occur at the sectoral level but may be considered as a suite of interventions with cross-sectoral linkages. They can also be prioritized based on their effects beyond emissions — such as societal benefits, economic considerations, reduction of near-term climate risks, interest in innovation to achieve breakthroughs in technologies of the future (e.g., carbon dioxide removal [CDR] or high-heat applications in industry), and many others. If implemented now, any emissions reduction intervention designed with careful consideration of trade-offs and benefits can ultimately help reduce near-term temperature rise, thereby preventing overshoot and the hitting of climate tipping points.

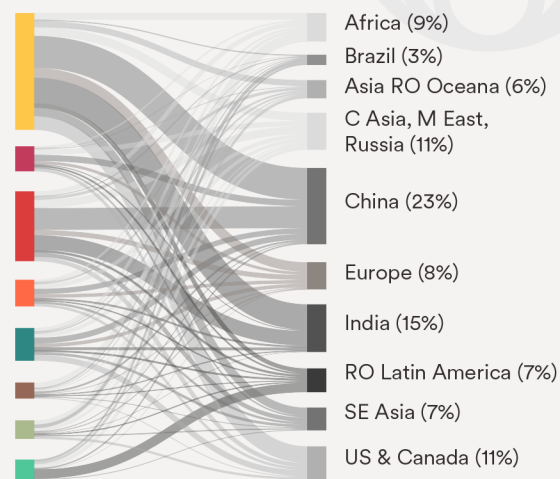
Philanthropy is at its best when we can collaborate and act on decisions informed by the latest in scientific understanding. Informed by data and facilitated engagement with a variety of social impact levers, philanthropy can continue to make targeted investments into a wide range of mitigation-focused opportunities that contribute to equitable outcomes at a sectoral and regional level. This report is meant as a resource to help funders and the broader climate solutions community examine the vast range of available emissions reduction measures that are urgently needed as we step up our ambition and climate change action in this decade.

FIGURE 2. CENTRAL PATHWAY RESULTS (EMISSIONS, SECTORS, GEOGRAPHIES)

Global mitigation by sector (GtCO₂e/yr)

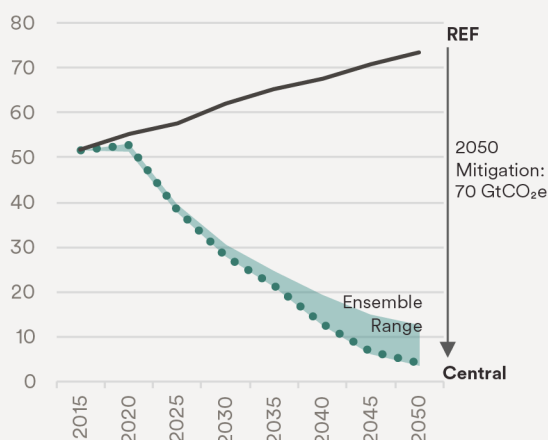


2050 mitigation by sector & geography (GtCO₂e)

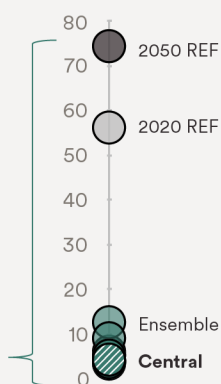


Total 2050 mitigation between the Reference and Central scenarios is around 70 Gt CO₂e spread out across sectors and geographies. While all regions must contribute to emissions reductions, there is variation in how each might contribute to sectoral reductions. Sector details are discussed more fully in the sections below. Note that technological CDR is from direct air capture and does not include natural CDR or BECCS. More on the potential role of CDR is discussed in a dedicated section below and in the Technical Summary.

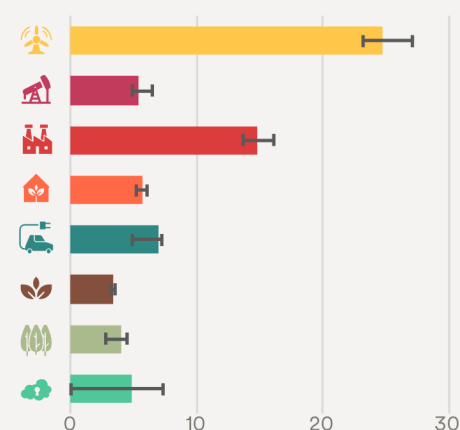
2015-2050 global emissions (GtCO₂e/yr)



2050 emissions (GtCO₂e)



2050 ensemble mitigation potential by sector & central scenario (GtCO₂e)



Total 2050 mitigation between the Reference and the Ensemble results are between 61 and 70 GtCO₂e (left). This Ensemble range represents outcomes of 16 scenarios that vary technological parameters that either incentivize or constrain the use of mitigation options while still achieving a 1.5° C-compatible pathway (although probabilities of meeting this target change). This range reflects changes that occur at the sectoral level (right). As constraints or incentives are deployed, the amount of mitigation in a particular sector fluctuates while also triggering changes in other sectors. Most scenarios in the Ensemble converge around the Central scenario, and differences are discussed throughout this report.

Introduction

The world remains far from meeting the primary goal outlined under the 2015 Paris Agreement on climate change: reducing greenhouse gas (GHG) emissions to keep global average temperature rise to well below 2° C by 2100 and making every effort to stay under 1.5° C. Current emissions are rebounding from a brief decline during the economic downturn related to the Covid-19 pandemic.¹ To get on track to meet the goal of the Paris Agreement, research suggests that GHG emissions should be roughly halved by 2030 on a trajectory to reach net zero by around midcentury.² Although these are global targets, every sector and country can and must contribute, especially higher-income countries that have a greater capacity to act. And while there are movements in this direction — as demonstrated by a series of updated pledges or nationally determined contributions (NDCs) as part of the ratcheting mechanism to the Paris Agreement — these efforts alone do not achieve a 1.5° C compatible pathway. Even in the most optimistic case, they have only a roughly 50% probability of limiting warming to 1.8° C, leaving a large gap throughout the century, especially in the shorter term, where a lack of ambition makes a temperature overshoot pathway highly likely.³

The body of scientific understanding of what lies ahead continues to grow — including with the release of the most recent set of assessment reports from the Intergovernmental Panel on Climate Change (IPCC). In particular, the Synthesis Report of the IPCC Sixth Assessment (Longer Report), published in March 2023, paints a grim picture of increased climate hazards and risks to ecosystems and humans if global warming reaches or exceeds 1.5° C. Each additional fraction of a degree increases the associated climate risks. In short, the Sixth Assessment Report argues that “any further delay in concerted anticipatory global action on adaptation and mitigation will miss a brief and rapidly closing window of opportunity to secure a livable and sustainable future for all.”

In this report, we identify the potential for various sectors distributed across 10 global geographies to pursue emissions reduction opportunities that would meet the Paris Agreement goals, with a focus on 2050. Using the integrated assessment model called the Global Change Analysis Model (GCAM), we developed a range of climate scenarios that build on the Representative Concentration Pathways—Shared Socioeconomic Pathways (RCP-SSP) scenario framework.⁴ Our scenarios are extensions to the RCP-SSP process; they include additional constraints to 1) better reflect the multiple benefits of sustainable development, technological progress, and the potential of behavioral change as reflected by ClimateWorks’ programmatic aims (see a detailed discussion of parameters in the Technical Summary), and 2) reflect the growing consensus regarding the level of ambition needed to reach net-zero carbon dioxide emissions by 2050.⁵

We selected parameters for testing through a co-production process with ClimateWorks’ sectoral experts to arrive at a Central, or anchoring, scenario. In addition to this Central scenario, we offer a new set of Ensemble scenarios that further test a selection of key parameters, allowing a better understanding of the options around which a pathway might be designed. This enables an informed discussion on a wider range of possible outcomes and reveals additional nuance, linkages, and trade-offs to climate change mitigation strategies.

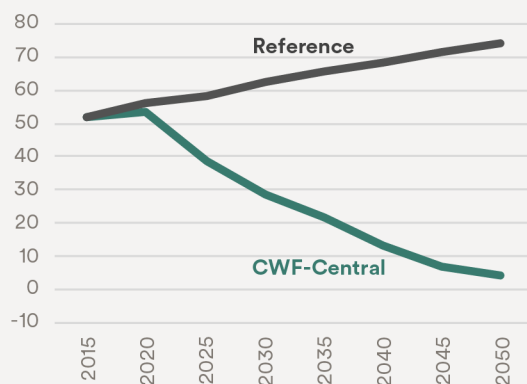
Every country can and must deliver their own contributions in order to meet global climate goals, especially higher-income countries that have a greater capacity to act. Our climate scenarios were developed with the open-source Global Change Assessment Model (GCAM) and designed in partnership with the Joint Global Change Research Center. As with previous reports, we make these findings available as a resource to help climate funders and others interested in climate change mitigation to identify priorities and help advance a vision for how to address and avoid the catastrophic risks associated with global warming.

High-level results

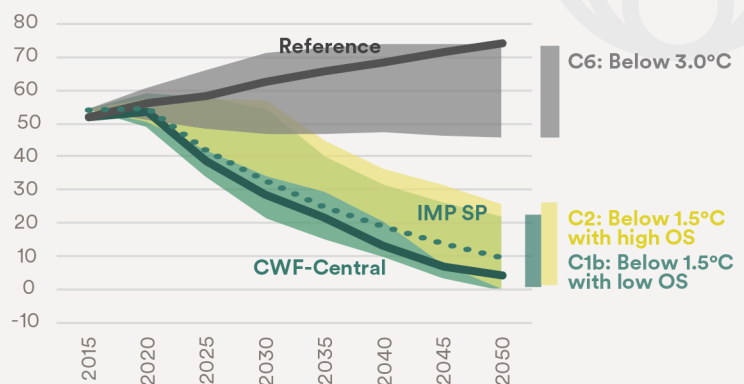
How have our results changed since our 2020 report “Achieving global climate goals by 2050: Actionable opportunities for this decade”? Findings are strikingly similar in the aggregate, but there are crucial developments within the scenario narratives and modeling capabilities. As seen in Figure 2 (above), total mitigation (the difference between a Reference case and our Central scenario) in 2050 remains at around 70 GtCO₂e, in line with the previous report. However, this masks a shift in results both in the Reference case and in the ambition of the Central scenario, which now achieves net-zero carbon dioxide emissions by 2050 — thus aligning results with other modeling efforts like those that support the reporting of the IPCC and the International Energy Agency. Comparisons to these modeling efforts are included in Figure 3, and more detailed comparisons at the sector level can be found in the Technical Summary. These new results are aligned, utilize one of the very same models used in IPCC reports (GCAM), and go a step further by incorporating philanthropic priorities both in the design of the narrative behind the Central scenario and in the Ensemble, which was built to address common questions posed from partners in the philanthropic community on the varying pathways that might achieve a Paris-aligned, 1.5° C outcome.

FIGURE 3: CWF CENTRAL SCENARIO COMPARISON

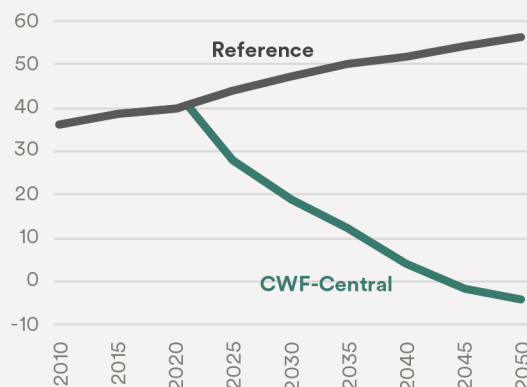
GCAM-CWF ref & central
(GtCO₂e/yr)



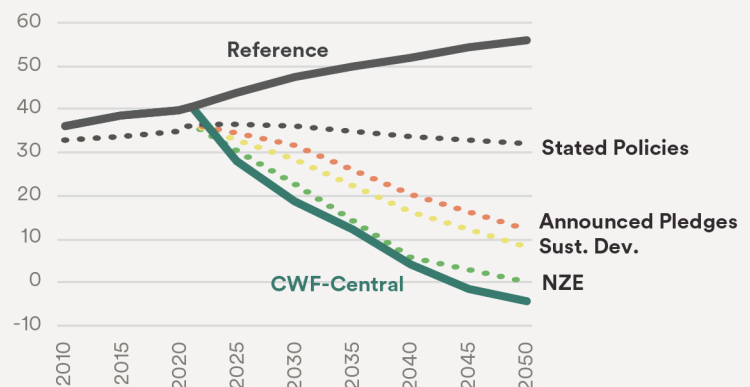
Comparison with IPCC AR6 WGIII scenario ranges
(GtCO₂e/yr)



GCAM-CWF scenarios
(energy GtCO₂/yr)



Comparison with 2022 IEA WEO
(energy GtCO₂/yr)



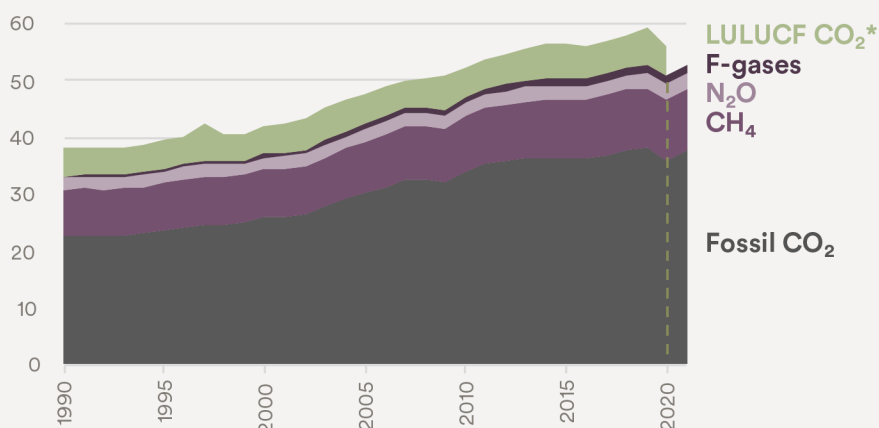
The IPCC AR6 WGIII Report includes multiple scenario sets grouped by temperature outcome and pathway characteristics. They also include Illustrated Mitigation Pathways (IMPs) which represent these sets. Here we show the C6, C2, and C1b pathways. The CWF Central scenario is closely aligned with the C1b pathways having a 1.5° C outcome with limited overshoot and is comparable to the associated IMP. Meanwhile, energy-related CO₂ outcomes are also highly comparable to the 2022 IEA WEO report outcome for its Net Zero Emissions (NZE) pathway. More comparisons including sector comparisons and discussion can be found in the Technical Summary.

Current state of emissions

Recent 2021 estimates report global emissions of just under 53 GtCO₂e.⁶ Land-use-related emissions are not yet reported, but the 10-year average would be an additional net 5 to 6 GtCO₂, putting the total closer to 58-59 GtCO₂e.⁷ In the following figures (4 and 5), we demonstrate how these emissions are cut within the GCAM model by source (e.g., fossil fuel), sector, emissions species (e.g., carbon dioxide, methane), and end uses. These emissions are the starting points for the scenarios that follow, which deploy mitigation solutions that curb these emissions and result in a net-zero, 1.5° C aligned pathway.

FIGURE 4: HISTORIC AND CURRENT EMISSIONS

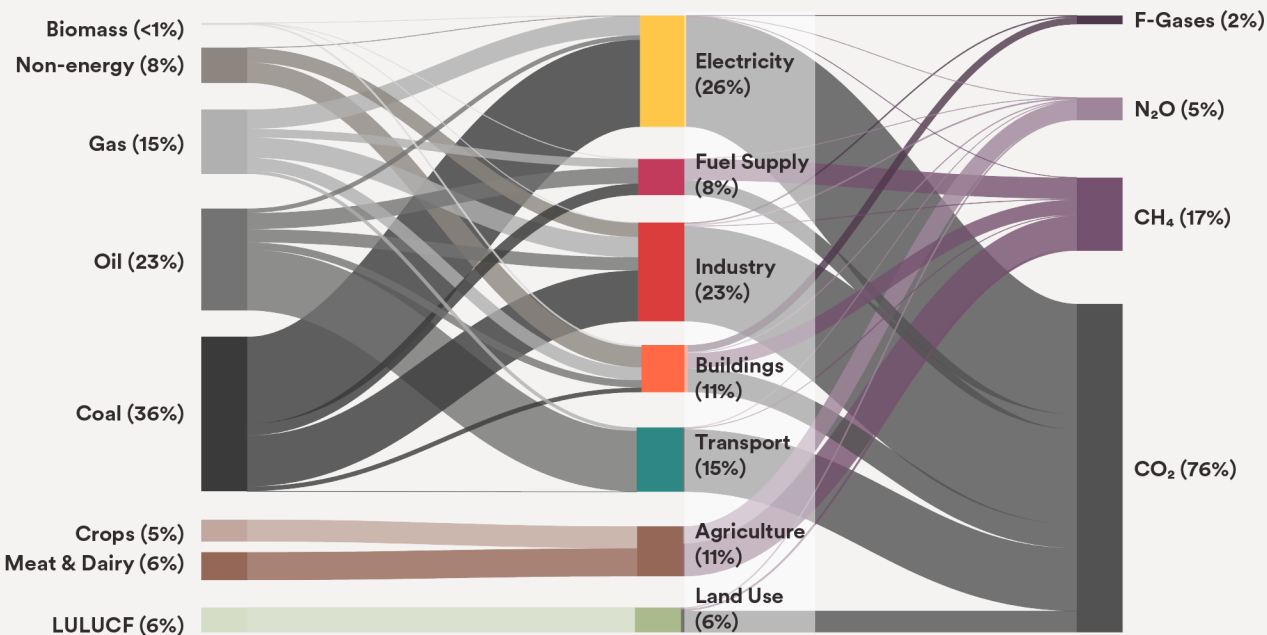
Global emissions by GHG 1990-2021 (GtCO₂e/yr)



Emissions in 2021 grew, showing a rebound from the slight dip seen in 2020 due to the global Covid-19 pandemic. This figure of historical emissions was adapted from the 2022 UNEP Gap Report. LULUCF emissions are from [Trends in Global CO₂ and Total Greenhouse Gas Emissions: 2021 Summary report](#).

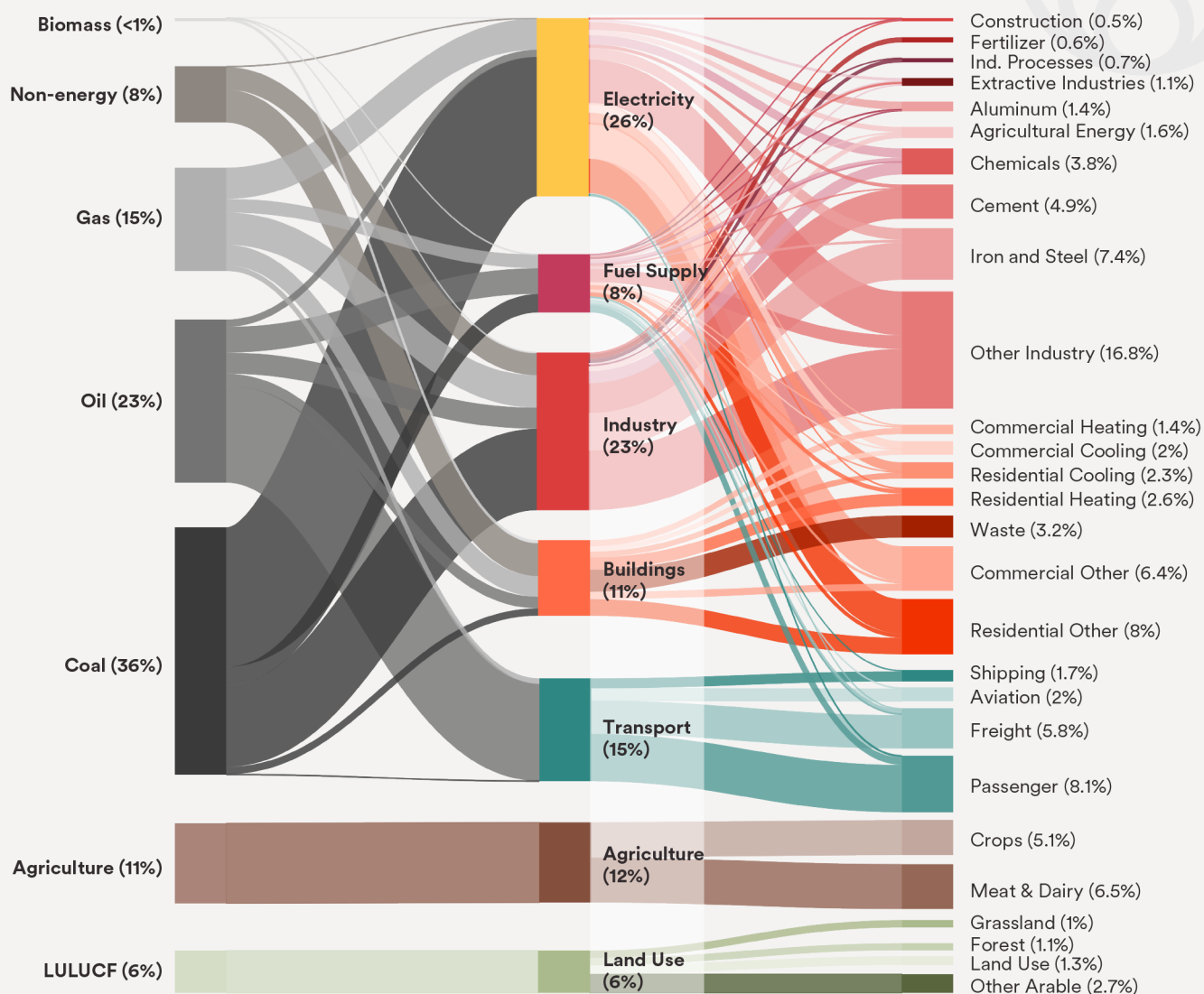
*LULUCF values for 2021 are not yet available, but these ranged between 5 and 7 GtCO₂ between 2010 and 2020.

2020 global emissions by sources, sector, and GHG within GCAM (total ~56 GtCO₂e)



Using GCAM 2020 values, we see the distribution of emissions across sources, sectors, and types of greenhouse gas. Note, however, that there is uncertainty around LULUCF emissions, and so depending on the data source, total emissions and their shares by gas might differ from those shown here.

FIGURE 5: 2020 GLOBAL GHG EMISSIONS SHARES BY SOURCES, SECTOR, AND END USES
(TOTAL ~56 GTCO₂E)



Here, we see how emissions flow to end-use sectors. Mid and upstream emissions associated with Electricity and Fuel Supply sectors are assigned to these end uses, thus showing the fuller scope of associated emissions. For example, Industry grows from around 23% when counting only direct fuel use to 39%, Buildings grows from 11% to 26%, and Transport from 15% to 18%. Land-use sectors have many subsectors and are simplified here, but more detail is provided in the sections below. Overlaps like these are discussed throughout this report.

The Central and Ensemble scenarios

In this report, we launch the ClimateWorks Scenario Ensemble (“Ensemble” for short), which contains 15 scenarios that isolate key parameters. This allows us to answer a variety of “what if” questions and provides an opportunity to test the robustness of the assumptions in our Central scenario. While we use our Central and Ensemble scenarios to help build our understanding of the potential solution space (i.e., what it takes in terms of mitigation required), we do not see them as prescriptive or a one-size-fits-all solution set. Instead, we consider these scenarios and their ongoing co-development process as a basis for deeper discussion on how transitions might occur across sectors and geographies. We continue to evolve our thinking and intend to update the Ensemble with additional scenarios (see “Future Research” in the Technical Summary).

Before discussing the details of the fuller Ensemble, it is important to review the narrative elements with which we designed our Central scenario. We attempted to evaluate programmatic aims from ClimateWorks and our philanthropic partners and match them with parameters within the GCAM model, all the while maintaining the goal of limiting the global mean temperature increase by the year 2100 to 1.5° C, with very limited overshoot. These are the same conditions used in the most ambitious scenarios in the recent IPCC Working Group III report.⁸ Several themes emerged from our engagement with relevant parties, including an emphasis on the pathway benefits, rapid technological change, the maintenance of a thriving land-use sector that prioritizes ecosystem protections, and the potential contribution of lifestyle changes. Table 1 highlights how these key themes are included within the scenario; the Technical Summary includes a longer list of sectoral changes.

TABLE 1: KEY NARRATIVE THEMES AND SECTORAL ELEMENTS EXPLORED IN THE GCAM-CWF SCENARIO

 Pathway Benefits	 Technology	 Sustainability	 Lifestyle Contributions
With so many potential ways to reach the end goal of limiting global warming to 1.5° C, the GCAM-CWF scenario seeks out the many potential benefits along the way. For example, this means the scenario aims to balance the use of land-based options and emphasizes the need for interventions that have multiple benefits.	The scenario underscores the importance of rapid technological deployment, and especially electrification wherever possible, in order to utilize a future zero-carbon grid. Meanwhile, deployment of efficiency measures allows space for the scaling of sustainably sourced bioenergy and other zero-emissions alternative fuel use where electricity is not available.	The scenario highlights the importance of maintaining a thriving land-use sector that aids in climate stabilization without sacrificing biodiversity. This means a more gradual ramping of changes to farmlands, forests, and other natural habitats. Further, there is a constraint placed on the total amount of bioenergy available, emphasizing the importance of scaling sustainable land-use practices.	Finally, the scenario also highlights the capacity of human behavior to change. This means that shifts in diets and other consumption patterns align with a future that focuses on sustainable development instead of continuing business as usual. However, such shifts are more complex than outlined in this scenario and must ultimately account for regional differences and equity considerations.

What parameters did we test in the Ensemble?

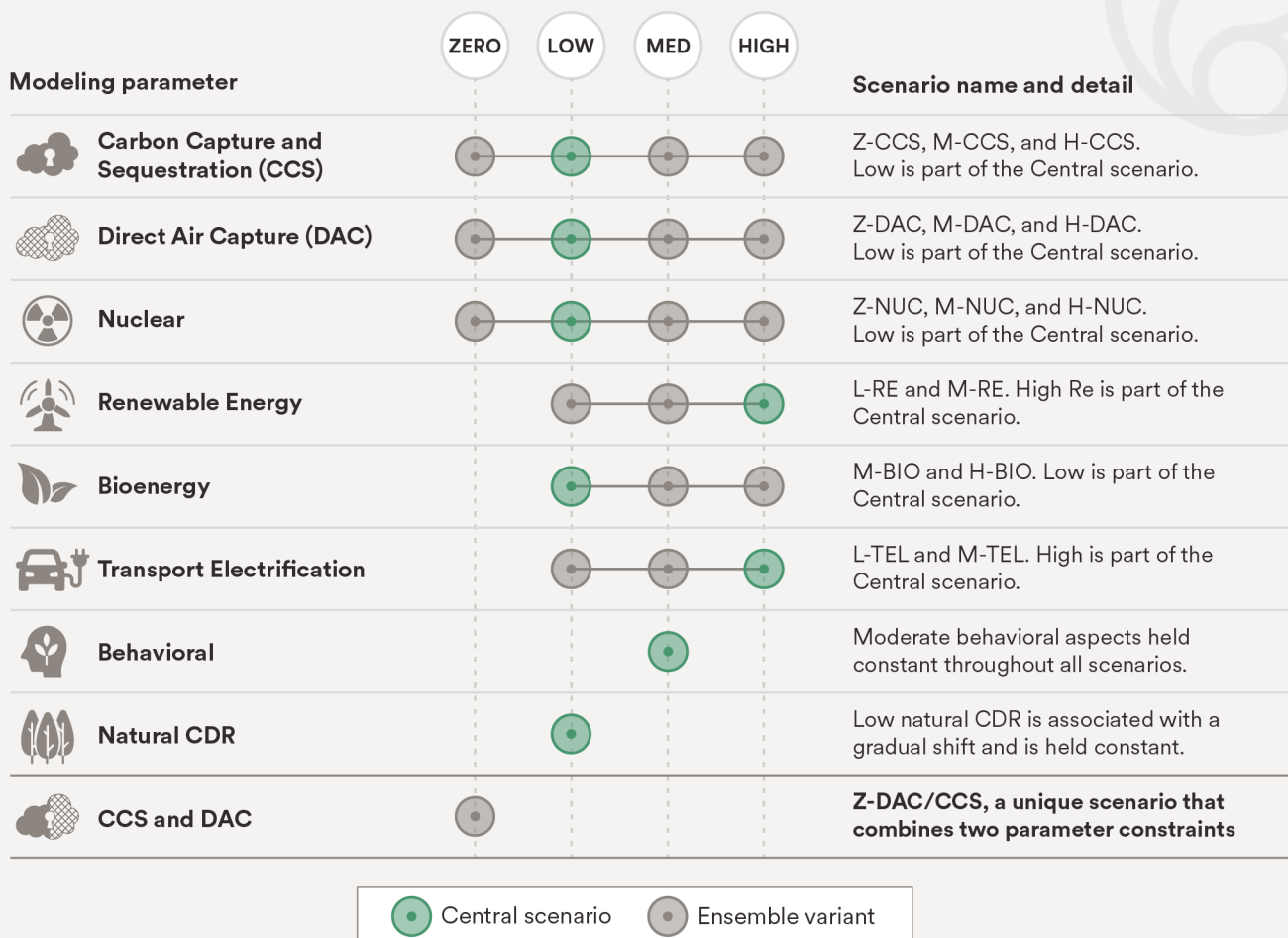
The ClimateWorks Global Intelligence team frequently receives “what if” questions from partners regarding the options for mitigation solutions. These questions often revolve around uncertainties in the pace and level of deployment of key technologies. Models like GCAM are fit-for-purpose in answering many of these questions through the development of constraint scenarios. For this report, we focused on the pace and deployment of six key groupings of parameters:

- bioenergy
- carbon capture and sequestration (CCS)
- technological carbon dioxide removal (CDR), including direct air capture (DAC)
- electrification for road transportation modes
- nuclear generation
- renewable energy (RE) Generation

The narrative elements in Table 1, including the importance of ecosystem protections (especially in forests) and inclusion of behavioral or lifestyle contributions, are included throughout the Ensemble, meaning each scenario variant holds equal or unchanged all other parameters, including these land use and behavioral contributions as depicted in Figure 6 below.

For each of the parameter groupings, we used a framework that varies deployment levels simplified as Low, Medium, or High. For several groupings, we constrained a technology completely, creating a Zero scenario. We acknowledge that there are differing opinions on what constitutes a low, medium, or high deployment level for technologies, as preferences vary across communities. Nonetheless, we attempted to model by consensus while using the Ensemble to test and evaluate differing mitigation options. For example, while our Central scenario highly constrains the use of bioenergy (part of ensuring ecosystem protections while also limiting the competition of land use for food versus for energy production), we also tested higher levels of bioenergy deployment to evaluate system trade-offs. In the simplified chart below (Figure 6), we identify the Central scenario parameters in green and each of the Ensemble variant scenarios in gray. This means that the Central scenarios can be considered to have Low CCS, Low DAC, Low nuclear, High RE, Low bioenergy, High electrification, Medium behavior change, and Low natural CDR. For each variant of the Ensemble, all other parameter assumptions (e.g., those in green) are held constant.

FIGURE 6: MODELING PARAMETERS FOR CENTRAL AND ENSEMBLE SCENARIOS



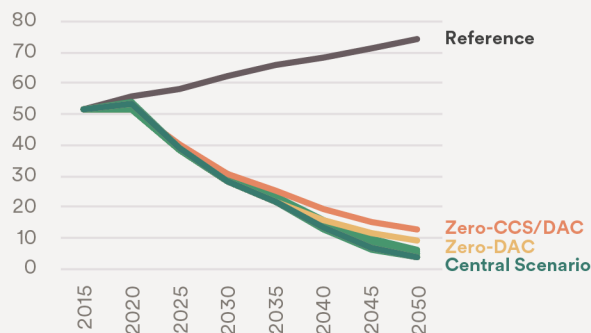
Importantly, two scenarios have a lower probability of achieving the 1.5° C outcome: the Z-DAC/CCS and the Z-DAC scenarios. See Figure 7 for details on temperature outcomes.

Ensemble emissions pathways and temperature results

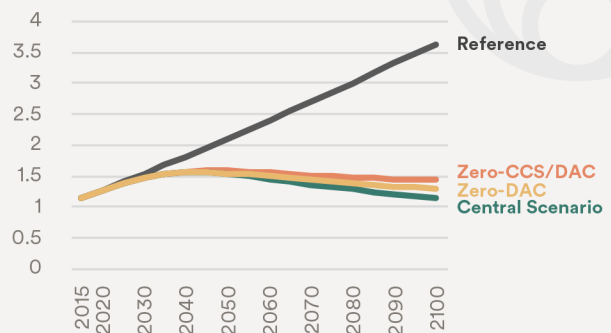
As mentioned, the overarching modeling goal was to maintain end-of-century temperature rise in line with the Paris Agreement target of limiting temperature rise to 1.5° C with limited overshoot. We also aimed to achieve net-zero carbon dioxide emissions by 2050 in line with other ambitious scenarios. GCAM is coupled with a simplified climate model known as Hector.⁹ Hector indicates that the Central scenario has an overshoot no greater than 0.06° C between 2035 and 2055. Outcomes for end of century are set at 50% probability. For a higher probability of limiting temperature increase to 1.5° C by 2100, the end result must therefore be lower than this 1.5° C threshold. The Central scenario and the bulk of the Ensemble result in a global mean temperature rise of around 1.2° C, thus achieving this higher probability of limiting temperature rise to 1.5° C or less. There are two exceptions: the Zero-DAC (direct air capture) and the Zero-DAC/CCS scenarios. The Zero-DAC scenario results in a 1.3° C outcome, which we consider still compatible with the Paris Agreement but having a lower probability. The Zero-DAC/CCS scenario results in just under 1.5° C in temperature rise and is associated with an overshoot of about 0.1° C (See figure 7 for emissions and temperature outcomes). This means that this scenario is closer to a 50% chance and therefore enshrines one of the most significant trade-offs: As carbon dioxide removal options are curtailed or completely constrained, there is a lower probability of meeting the 1.5° C target. This finding is confirmed in the Synthesis Report of the IPCC Sixth Assessment Report, which states that “CDR will be necessary to achieve net-negative CO₂ emissions” and that “net zero GHG emissions, if sustained, are projected to result in a gradual decline in global surface temperatures after an earlier peak.”¹⁰

FIGURE 7: GLOBAL EMISSIONS PATHWAYS AND TEMPERATURE OUTCOMES

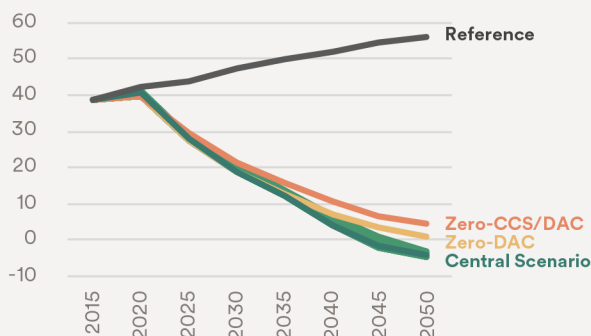
Global emissions pathways (GtCO₂e)



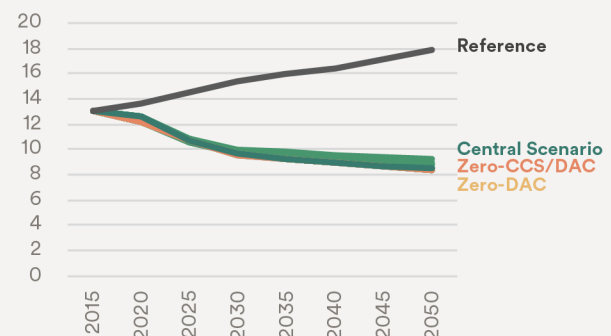
Global mean temperature outcomes (°C)



Global carbon dioxide emissions pathways (GtCO₂)



Global non-CO₂ GHG emissions pathways (GtCO₂e)



These figures show emissions and temperature outcomes for the Ensemble scenarios. The Global mean temperature outcome in the Central scenario is 1.2° C in 2100. This outcome is a decline from a peak temperature rise of slightly above 1.5° C seen between 2035 and 2055. Other Ensemble scenarios reach similar outcomes except for the Zero-DAC and Zero-CCS/DAC scenarios which have higher associated temperatures. This low-temperature outcome suggests that the Central scenario (and those with similar temperature outcomes) is consistent with C1b scenarios as outlined in the recent Working Group III report from the IPCC's Sixth Assessment Report.

Mitigation opportunities by sector

Moving from a global perspective to more granular details of sectors and geographies while maintaining consistency toward achieving a 1.5° C target requires the use of sophisticated tools like integrated assessment models. These tools (of which GCAM is one of many) allow an examination of the trade-offs inherent in any pathway toward 1.5° C. For example, there are interactions between sectors in how energy systems produce, refine, transport, and ultimately use various fuels that also impact how we protect or cultivate our land systems. This implies the need to examine the linkages among sectors at a narrative level when developing a scenario, to avoid treating a specific element — such as a specific sector, fuel source, or geography — in isolation. Doing so could overlook important physical and temporal dependencies that arise in ambitious pathways. Ultimately, any effective climate strategy must consider multiple dimensions such as equity, costs, benefits, and societal acceptance of various measures.

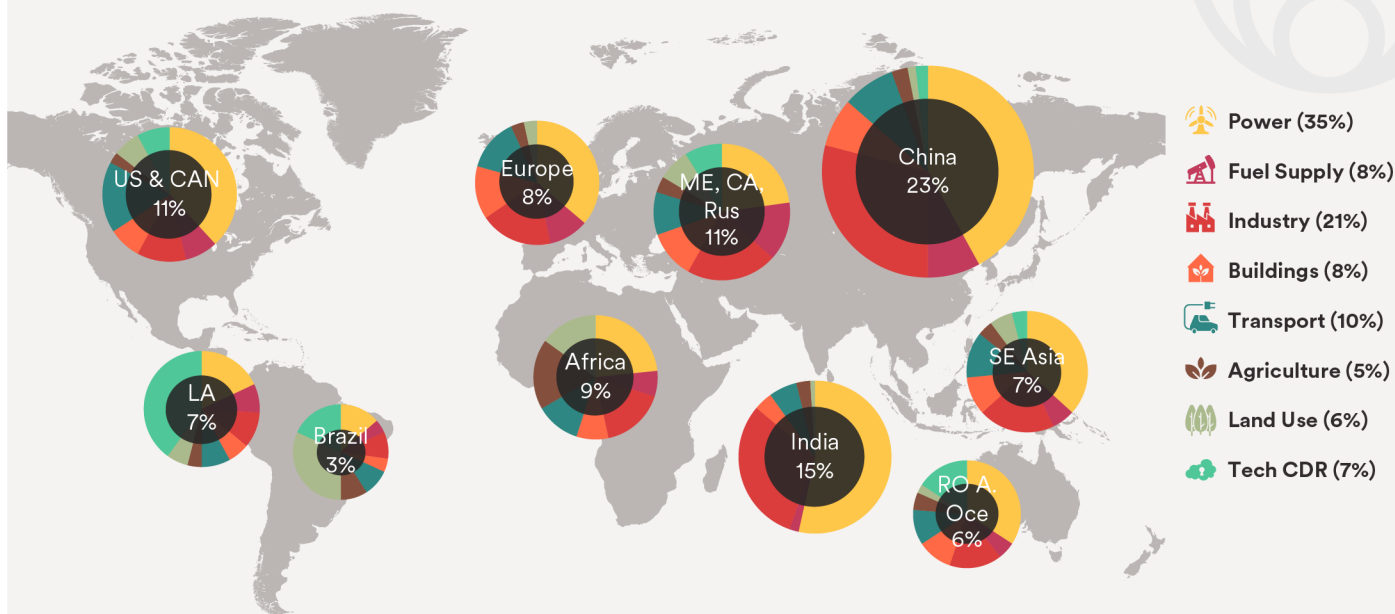
For each sector, we provide two sections: one on the GHG emissions results comparing a Reference case with our Central scenario, and a second that includes additional results from the Ensemble particular to each sector and a discussion of insights and pathway implications. We also include sections that discuss the overlap between sectors, an important aspect to mitigation. This becomes obvious when one considers that some sectors are inputs to others. For example, electricity is an input to end-use sectors including industry, buildings, and transportation. Typically these are split in reporting, with electricity emissions referred to as *indirect*, and emissions associated with end uses (including on-site and process-related emissions) referred to as *direct*. We report in this way for each of the sectors, treating each as separate. However, we also reference indirect emissions and provide a section that describes the fuller scope of emissions, combining direct and indirect emissions for energy-related sectors on page 31 and for land-use sectors on page 38.

Additional consideration is provided for the different types of greenhouse gas. We report all emissions, calculating carbon dioxide equivalents using 100-year global warming potentials according to [AR5 values](#).¹¹ This allows values to be normalized and reported together. In tables we indicate what portion of the emissions are from carbon dioxide and what portion are from other pollutants, which we refer to as *super pollutants*.

We demonstrate all this overlap in Figures 4 and 5 (above), Sankey diagrams that showcase a fuller spectrum of ways in which we can separate out streams of greenhouse gas emissions. We include sector-specific Sankey diagrams for each sector, and we have placed larger representations of these in the Technical Summary for further examination.

Taking the larger view, Figure 8 (below) shows 2050 global mitigation downscaled to sectors and geographies. While the GCAM model contains 32 geographies (see Technical Summary TS Table 6 for geographic details), we aggregate these into 10 geographies. In the following sections, we provide data for each sector at the global and geographic level. Figure 9 shows a comparison between results for 2030 and for 2050.

FIGURE 8: 2050 MITIGATION BY SECTOR AND GEOGRAPHY IN CENTRAL SCENARIO
(TOTAL MITIGATION AROUND 70 GTCO₂e)

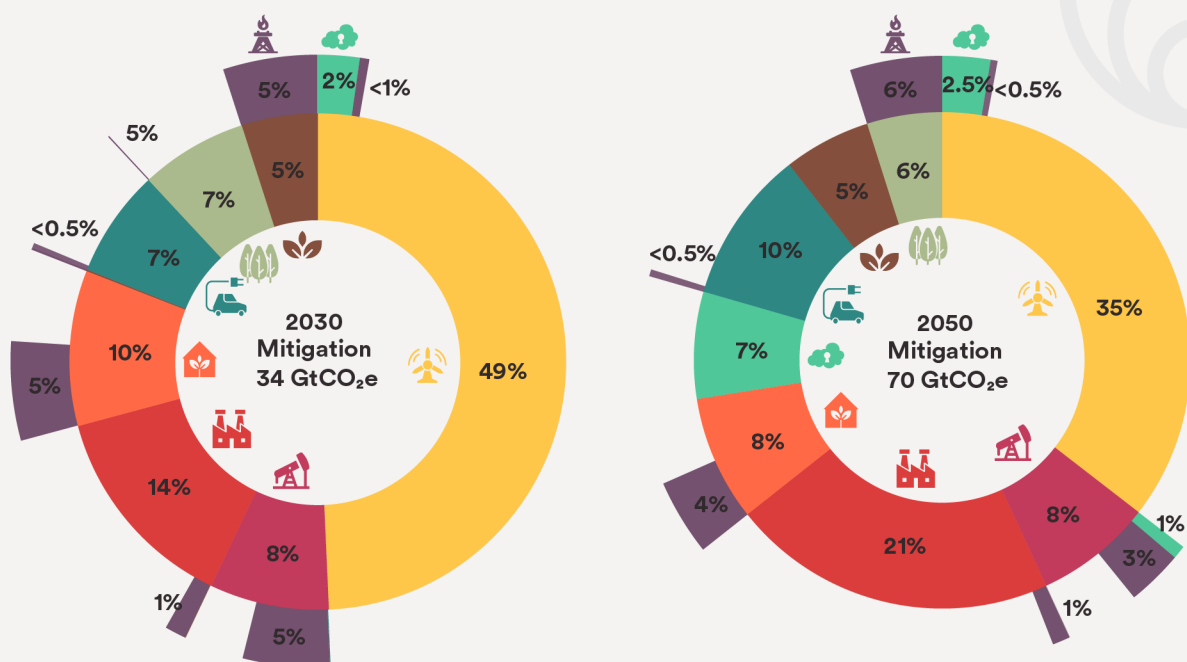


2050 total mitigation by region (GtCO₂e)

	Global	Africa	Asia (RO) and Oceania	Brazil	C Asia, M East, Russia	China	Europe	India	Latin America (RO)	SE Asia	U.S. & Canada
Electricity	24.8	1.4	1.3	0.3	1.8	6.8	2.1	5.4	0.9	1.8	2.9
Fuel Supply	5.3	0.4	0.2	0.1	1.1	1.3	0.6	0.2	0.4	0.3	0.6
Transport	7	0.7	0.4	0.2	0.8	1.3	0.8	0.6	0.4	0.6	1.3
Industry	14.8	1	0.6	0.2	1.7	4.7	1.1	3.1	0.5	1	0.9
Buildings	5.7	0.5	0.4	0.1	0.9	1.2	0.8	0.4	0.3	0.5	0.6
Land Use	4	0.9	0.1	0.7	0.6	0.2	0.2	0.1	0.3	0.3	0.5
Agriculture	3.4	1.1	0.2	0.2	0.3	0.4	0.2	0.3	0.2	0.2	0.2
Tech CDR	4.9	0	0.6	0.4	0.7	0.3	0	0	2	0.2	0.6
TOTAL	69.9	6.1	3.9	2.2	7.9	16.1	5.8	10.1	5.1	4.9	7.7

Total 2050 mitigation between the Reference and Central scenarios is around 70 GtCO₂e spread out across sectors and geographies. While all regions must contribute to emissions reductions, there is variation in how each might contribute to sectoral reductions. Sector details are discussed more fully in the sections below. Note that Technological CDR is from Direct Air Capture and does not include natural CDR or BECCS. More on the potential role of CDR is discussed in a dedicated section below and in the Technical Summary.

FIGURE 9: 2030 AND 2050 EMISSIONS REDUCTIONS BY SECTOR AND CROSS-SECTORAL LINKAGES



2030 mitigation ~34 Gt		Share	GtCO ₂ e
	Electricity	49.3%	16.9
	Fuel Supply	7.8%	2.7
	Industry	13.8%	4.7
	Buildings	10.1%	3.5
	Tech CDR	0.1%	0.04
	Transport	7.0%	2.4
	Forest and Land Use	7.0%	2.4
	Agriculture	5.0%	1.7
Cross-Sectoral			
	Non-CO ₂	16.6%	5.7
	BECCS	2.2%	0.8

2050 mitigation ~70 Gt		Share	GtCO ₂ e
	Electricity	35.5%	24.8
	Fuel Supply	7.6%	5.3
	Industry	21.2%	14.8
	Buildings	8.2%	5.7
	Tech CDR	7.0%	4.9
	Transport	10.0%	7.0
	Forest and Land Use	5.7%	4.0
	Agriculture	4.9%	3.4
Cross-Sectoral			
	Non-CO ₂	13.5%	9.5
	BECCS	3.3%	2

Compared with the Reference scenario, the Central scenario sees mitigation totaling around 34 GtCO₂e by 2030 and 70 GtCO₂e by 2050, divided among multiple sectors. Due to path dependencies in the scenario narrative, the Electricity sector reduces emissions more quickly, allowing end-use sectors to maximize reductions through beneficial fuel switching toward electrified sources. All sectors reduce emissions significantly over time and are required to limit global mean temperature rise.

Electricity

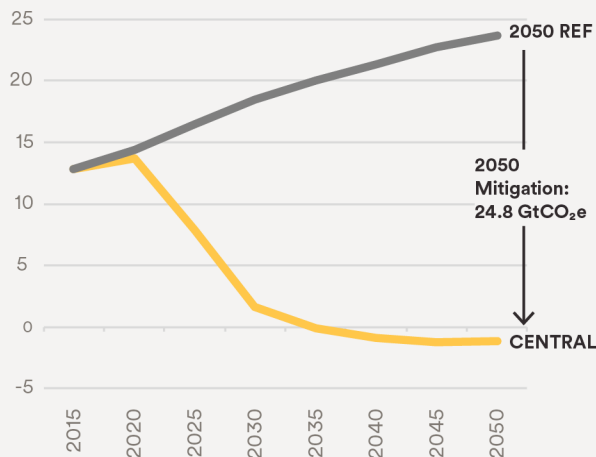
In 2020 direct emissions from electricity production, with its heavy reliance on coal, accounted for more than 14 GtCO₂e, or around 26% of global emissions. In the GCAM Reference case, these emissions could grow to roughly 24 GtCO₂e by 2050, driven by rapid projected growth in electricity use over the next three decades. With an aim to achieve global net-zero carbon dioxide emissions by 2050, the electricity sector in the Central scenario goes beyond many other sectors, achieving net zero by 2035 and being net negative thereafter. This allows rapid end-use electrification, which benefits from a zero-emissions grid. With full decarbonization of this sector in the Central scenario coupled with limited use of CDR technologies in the form of bioenergy with carbon capture and storage (BECCS), this sector could achieve emissions reductions of roughly 17 GtCO₂e by 2030 and 25 GtCO₂e by 2050, relative to a Reference case. This would make this sector the most significant contributor to overall emissions reductions while also enabling reductions in electrifying sectors.

Even with the remarkable increase in renewable energy (RE) capacity and generation in recent years, as well as the positive forecasts renewables have for the next few years, renewable power capacity would need to expand rapidly to achieve such a scenario. RE totals roughly 50% by 2030 and exceeds 70% by 2050 when one includes associated RE storage. Unabated fossil generation (or traditional thermal fossil generation), which stands at roughly two-thirds of generation in 2020, is reduced to only 10% by 2030 and 0% by 2050 through rapid decommissioning or retrofitting with CCS. Such use of fossil CCS is seen as a temporary solution in the Central scenario, and it loses share progressively over time as it is replaced by zero-emissions generation sources. In 2030 fossil CCS makes up just over 20% of generation; this is reduced to 13% by 2050 and further thereafter. Note that fossil CCS in the power sector loses share over time because not 100% of emissions are captured.

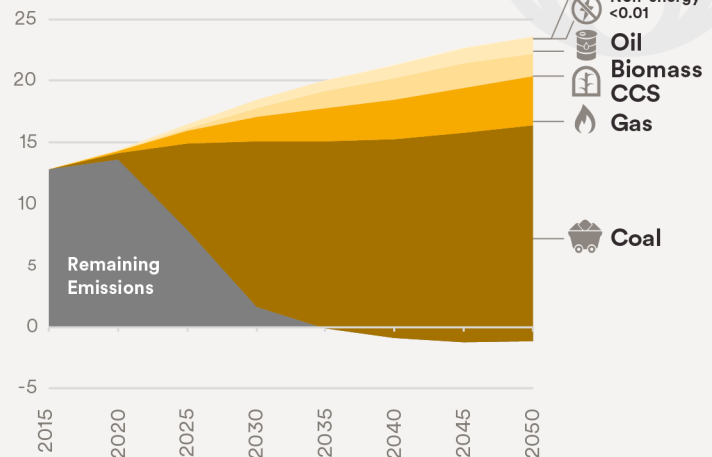


FIGURE 10: POWER SECTOR

Global power emissions (GtCO₂e/yr)



Mitigation by source (GtCO₂e/yr)



2050 total mitigation (solution space) GtCO₂e by region

	Global	Africa	Asia (RO) and Oceania	Brazil	C Asia, M East, Russia	China	Europe	India	Latin Am (RO)	SE Asia	U.S.A. & Canada
Coal	17.6	0.5	0.9	0.1	0.3	6.1	1.5	5.0	0.2	1.1	1.8
Gas	4.0	0.5	0.4	0.1	0.9	0.1	0.3	0.2	0.3	0.5	0.7
Oil	1.4	0.3	0.1	0.0	0.5	0.0	0.1	0.2	0.2	0.1	0.0
Tech. CDR	1.8	0.1	0.0	0.0	0.1	0.6	0.2	0.0	0.2	0.1	0.3
Cross-Sectoral											
Non-CO ₂	0.3	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
TOTAL	24.8	1.4	1.3	0.3	1.8	6.8	2.1	5.4	0.9	1.8	2.9

In 2050, compared with a Reference scenario, the Central scenario reduces electricity emissions by around 25 GtCO₂e. This is around 35% of total mitigation. Totals might have a slight mismatch due to rounding.

Electricity Ensemble results

There is significant variation across pathways for the electricity sector in the Ensemble. By 2050 the total difference in emissions outcomes has a range of 4 GtCO₂e between the highest and lowest mitigation scenarios (see Figure 10). Such large variation is due to the range of choices for generating technologies in the sector. For example, the High and Medium bioenergy scenarios (reported as H-BIO and M-BIO) achieve the greatest emissions reductions by 2050, with -3.6 and -2.3 GtCO₂e, respectively, by 2050 due to increased use of BECCS. Two scenarios from our ensemble do not achieve net-negative emissions in this sector by 2050: the Z-CCS and Z-DAC/CCS scenarios, which result in emissions of roughly 0.5 GtCO₂e by 2050. In such scenarios, BECCS is eliminated completely.

Transformation in the power sector includes simultaneous emphasis on zero-emissions generating technologies, a scaling of output to meet increased demand, and grid stability mechanisms. Unabated fossil fuels make up roughly two-thirds of generation today. In the Ensemble scenario, when RE prices are assumed to be higher (as is the case in the L-RE and M-RE scenarios), the use of CCS and nuclear rise to maintain a zero-emissions grid. This also occurs when barriers like price or preference result in emphasized use of nuclear and CCS (as in the M/H-NUC and M/H-CCS scenarios). BECCS increases only in the medium and high bioenergy scenarios (M-BIO and H-BIO), resulting in the largest amount of carbon dioxide removal. These are the only scenarios in which unabated fossil continues to operate above 1%, with the M-BIO scenario at 1% and H-BIO scenario at 2%. Hydrogen plays a very limited role but could be investigated further for its use in conjunction with other energy storage options (a research area we are currently exploring). RE including associated storage exceeds 80% of generation when nuclear and CCS are restricted, as is the case in the Z-NUC and Z-DAC/CCS scenarios. Taken together, this variation implies a large degree of choice in pathway outcomes while retaining a near-zero-, zero-, or negative-emissions grid.

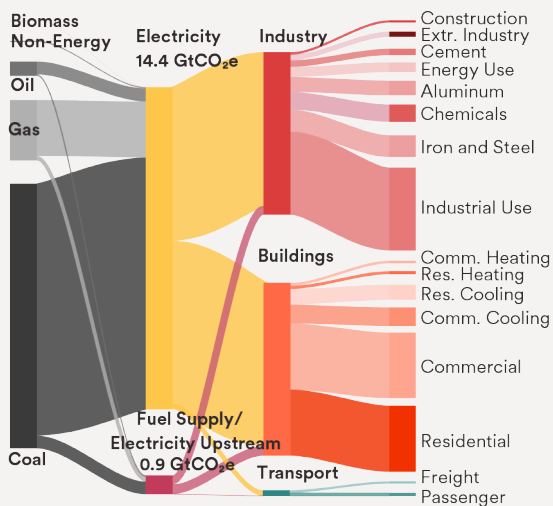
Electricity sector: insights and pathway implications

Transitioning the electricity sector is pivotal to any long-term climate target due to the necessity of both reducing emissions and building out the sector's potential to deliver abundant, emissions-free energy to homes, businesses, vehicles, and industries. In all Ensemble scenarios, electrification across these categories brings the share of electricity from less than one-quarter of final energy use today to more than half by midcentury. This means that livelihoods and economies will become increasingly reliant on this sector.

The transition from today's fossil-fuel-dependent grid to a net-zero emissions grid is essential — and the quicker the better to avoid a transfer of emissions from one source to another. This implies concerted near-term action in this sector to push out fossil-fuel generation, pull in and scale renewables and other zero-emissions generating technologies, and deploy improvement mechanisms that ensure reliability and resiliency of the grid. The Ensemble shows that the technological mix can take many forms while still resulting in a near-zero-, zero-, or negative-emissions grid. Such variation signals significant flexibility for weighing options, which in turn allows for additional considerations. For example, a pathway might include considerations for how generating technologies might impact livelihoods at a local level and account for issues such as energy burden and access, impacts on land, labor implications, and infrastructure investments needed.

FIGURE 11: POWER SECTOR DASHBOARD

a. 2020 power emissions flows (15.3 GtCO₂e of associated emissions)



a. This figure shows the flow from direct source to electricity and upstream fuel supply, continuing to sectors and finally attributed to end uses. For an in-depth view of this Sankey flow as well as detailed amounts of emissions, please refer to the Technical Summary (TS Table 3).

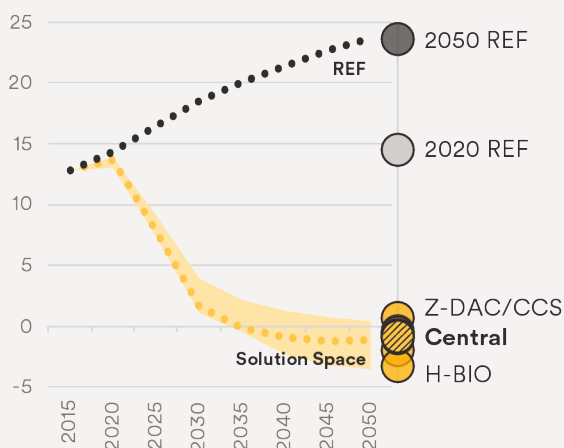
b. The gray dotted line displays the Reference case and the yellow line displays the Central scenario. The yellow shaded area represents the range of values for the full Ensemble. The scatter plot on the right takes the 2050 values of this graph displaying the Ensemble and Central scenarios and Reference case for 2020 and 2050.

c. The graph shows the change in the generation mix of electricity from 2015 to 2050. The Reference case is shown by the dark dotted line. In comparison, the Central scenario grows 43% more than the Reference case by 2050 due to larger growth in electrification, but this change varies across the Ensemble. The scatter plot on the right presents an additional view of the 2050 values of this graph, as well as the 2020 Reference case point.

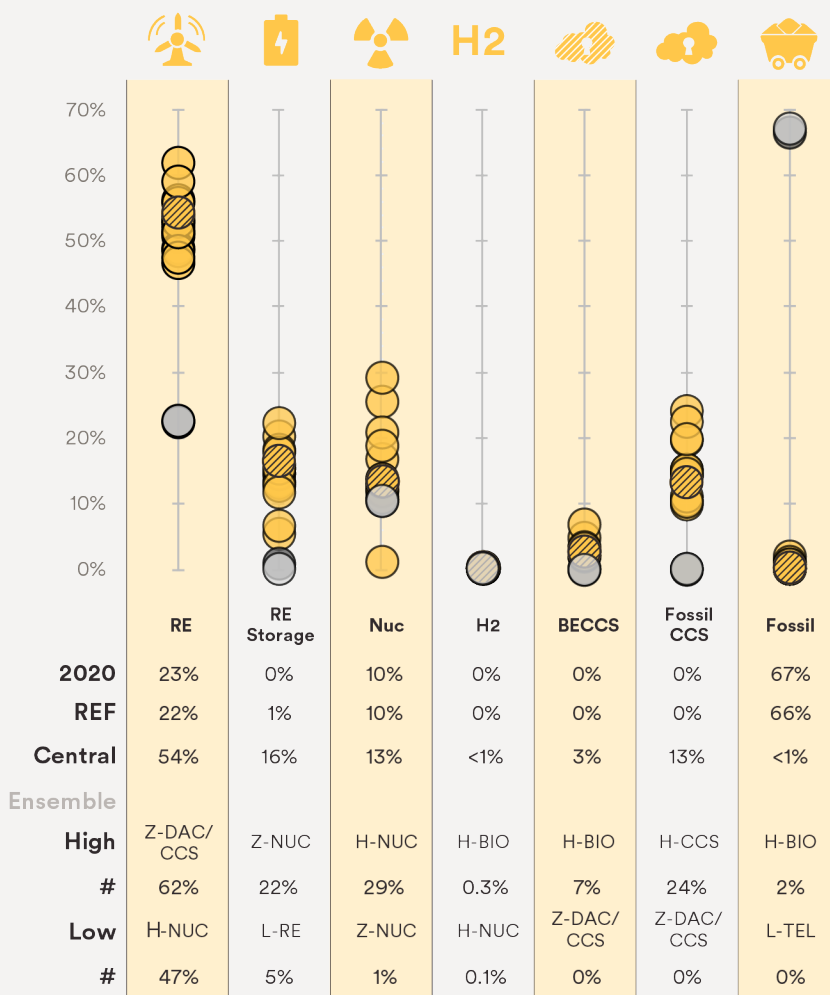
d. This shows 2050 generation shares by technology across the Ensemble as well as a comparison with the Reference case and the 2020 values. The table highlights the highest and lowest scenario with its value across the Ensemble showing variation based on scenario narrative.

● 2050 REF ● 2020 REF ● Central ● Ensemble

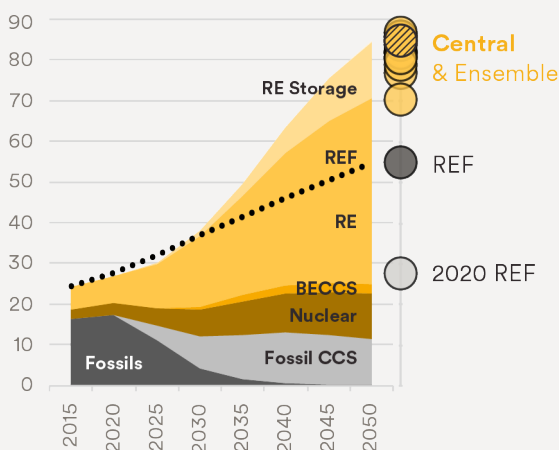
b. 2015-2050 electricity emissions (GtCO₂e/yr)



d. 2050 other Ensemble scenarios (GtCO₂e/yr)



c. Generation by source (1000 TWh)



Fuel Supply

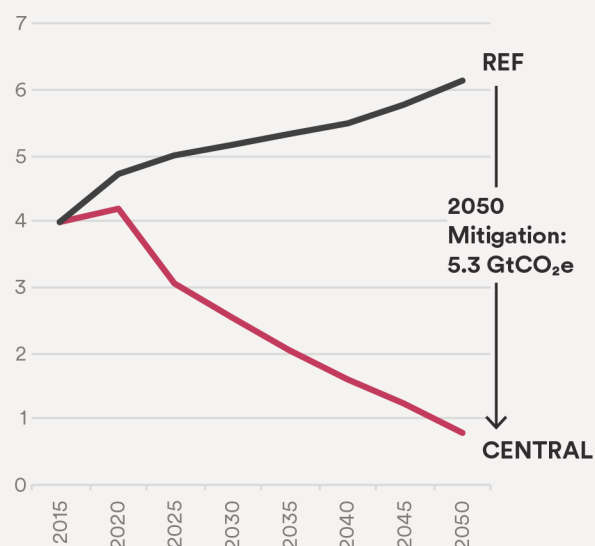
In 2020 emissions associated with fuel supply (the extraction, processing, refining, and distribution of fuels — mostly coal, oil, and gas) were roughly 4.7 GtCO₂e.¹² This includes around 2.8 Gt of super pollutant (non-CO₂) emissions, mostly methane from venting and leaks in oil and gas extraction and distribution processes as well as from coal mine leaks. The remaining 1.9 Gt of emissions consist of CO₂ associated with the refining of fuels and feedstocks for use in end-use sectors and electricity generation, as well as the transportation of fossil fuels. Overall, this sector comprises around 8% of total global emissions in 2020 and is projected to increase to more than 6 GtCO₂e by 2050, or around 28% in a Reference case.

Demand-side measures like electrification can help reduce emissions in this sector by reducing future demand. While such measures take time to scale, there are other technological solutions to deploy in the meantime — including measures that reduce the unnecessary and costly leakage of methane, deploy more efficient refining methods, and promote the development of CCS. Together, these actions account for almost 3 GtCO₂e of reductions in 2030 relative to a Reference case (which equates to roughly halving emissions from 2020), and more than 5 GtCO₂e by 2050 (around 7.5% of total mitigation by that year).

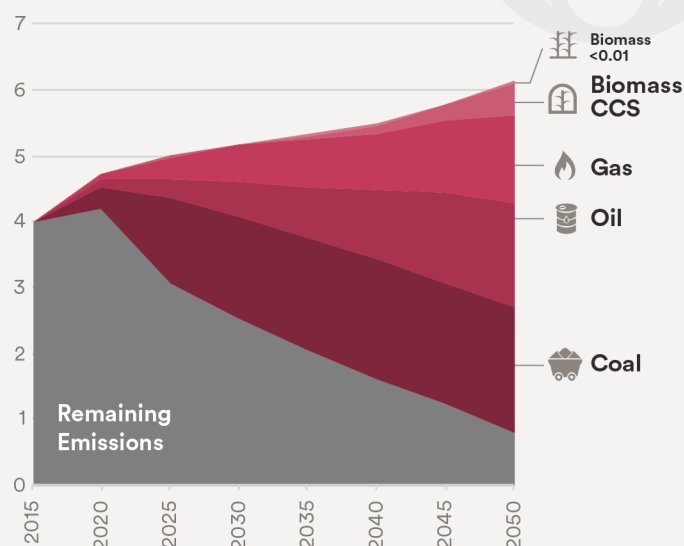


FIGURE 12: FUEL SUPPLY SECTOR

Global fuel supply emissions
(GtCO₂e/yr)



Mitigation by source
(GtCO₂e/yr)



2050 total mitigation by region (GtCO₂e)

	Global	Africa	Asia (RO) and Oceania	Brazil	C Asia, M East, Russia	China	Europe	India	Latin America (RO)	SE Asia	U.S.A. & Canada
Coal	1.9	0.1	0.1	0.0	0.4	0.7	0.2	0.0	0.0	0.1	0.3
Oil	1.6	0.2	0.1	0.0	0.3	0.3	0.1	0.2	0.1	0.1	0.2
Gas	1.3	0.1	0.1	0.0	0.4	0.2	0.2	0.0	0.2	0.1	0.1
Tech. CDR	0.5	0.0	0.0	0.0	0.1	0.2	0.1	0.0	0.0	0.0	0.0
Cross-Sectoral											
Non-CO ₂	2.1	0.1	0.1	0.0	0.6	0.3	0.2	0.0	0.2	0.2	0.4
TOTAL	5.3	0.4	0.2	0.1	1.1	1.3	0.6	0.2	0.4	0.3	0.6

In 2050, compared with a Reference scenario, the Central scenario reduces Fuel Supply emissions by around 5.3 Gt CO₂e. This is around 8% of total mitigation. Fuel Supply sectors refer to the extraction, processing, refining, and transmission of fuels. Totals might have a slight mismatch due to rounding.

Fuel supply Ensemble results

By 2050, emissions across the Ensemble for fuel supply range between -0.4 and 1.3 GtCO₂e per year (see Figure 12). H-BIO is the most ambitious scenario in fuel emissions reductions, followed by the Low Transportation Electrification (L-TEL) scenario, and both reach below-zero emissions by 2050. Meanwhile, the M-DAC and H-DAC scenarios have the highest emissions remaining by 2050, at 1.3 GtCO₂e. Total emissions from the Central scenario by 2050 are 0.8 GtCO₂e, slightly above the ensemble's mean (0.7 GtCO₂e).

Overall, within the Ensemble, we see comparable results with low-energy-demand scenarios seen in other analyses where primary energy consumption declines. The amount of potential increase or decrease in energy consumption, which has a direct impact on this sector, is subject to debate, as it includes tensions among such issues as equity in economic development, energy access, use of efficiency, diffusion of key technologies, and the role of behavioral change. Essentially, the push and pull of policies that impact interventions in other sectors will have a large impact on this sector. Beyond shifts in end-use demand, supply-side measures like methane emissions reductions are essential and make up nearly 40% of related mitigation by 2050, as seen in Figure 12 for non-CO₂. Such measures apply not only to oil and gas extraction but also to methane related to coal mining.

Fuel supply sector: insights and pathway implications

Transitioning the fuel supply sector will require a combination of upstream supply-side measures, productivity/efficiency, and emissions mitigation measures in the midstream processing of fuels. Additionally, it will require an overall demand reduction for fossil fuel use in end-use and electricity sectors. Strategies for this sector have traditionally focused on reducing demand for fossil fuels, which in turn reduces emissions associated with production and processing of those fuels. However, there is growing awareness that supply-side measures have a high value in the interim, as they can reduce and eventually eliminate sources of emissions — including methane leakage, which occurs throughout fossil fuel extraction, processing, and distribution cycles.

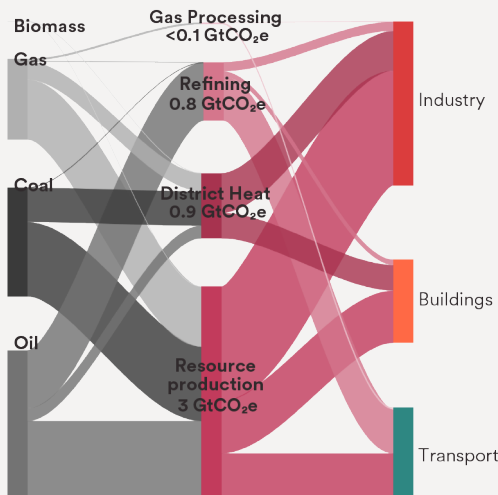
Methane is a powerful greenhouse gas with many times the warming effect of carbon dioxide, but delivered over a shorter time span. Recent efforts have culminated in the [Global Methane Pledge](#), which aims to curb methane by 30% by 2030 and includes methane sources from fossil fuel extraction and processing. As mentioned, in 2020 non-CO₂ emissions were responsible for roughly 3 Gt of the 4.7 GtCO₂e of emissions associated with this sector, and methane made up around 99% of these non-CO₂ emissions. Reductions could stave off warming in the shorter term, thereby reducing the size of an overshoot of 1.5° C temperature targets.¹³

Beyond methane, there are carbon dioxide emissions associated with the processing and refining of fuels. Such emissions can be curbed through a combination of increased productivity and efficiency measures, the use of waste and alternate zero-carbon fuels for heat and feedstocks, and the deployment of CCS.

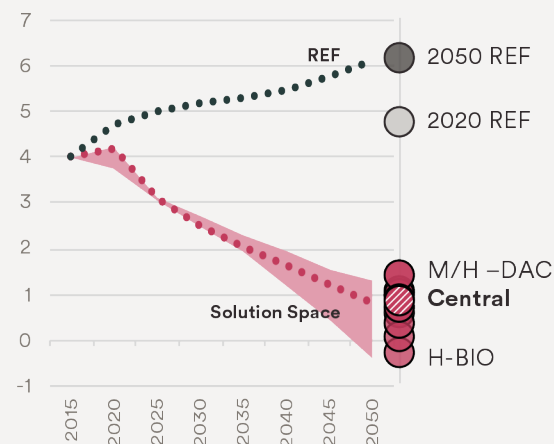


Fuel Supply

a. 2020 fuel supply emissions flows (4.7 GtCO₂e/yr)



b. 2015-2050 fuel supply emissions (GtCO₂e/yr)



c. Final energy demand by source (EJ)

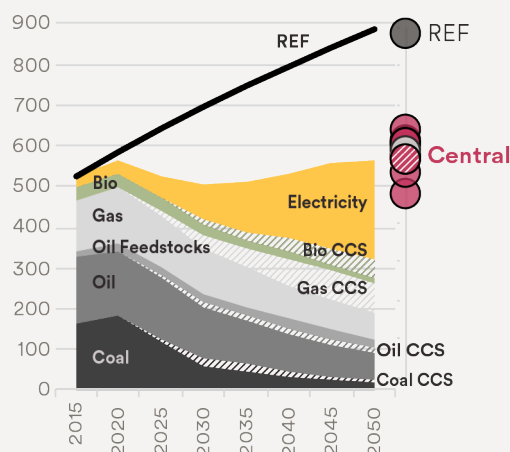


FIGURE 13: FUEL SUPPLY SECTOR DASHBOARD

a. This figure shows the CO₂e fuel supply flow from direct source to end uses and last to sectors. For an in-depth view of this Sankey flow as well as detailed amounts of emissions, please refer to the Technical Summary (TS Table 3).

b. The gray dotted line displays the Reference case and the pink line displays the Central scenario. The pink-shaded area represents the range of values for the full Ensemble. The scatter plot on the right takes the 2050 values of this graph displaying the Ensemble and Central scenarios and Reference case for 2020 and 2050.

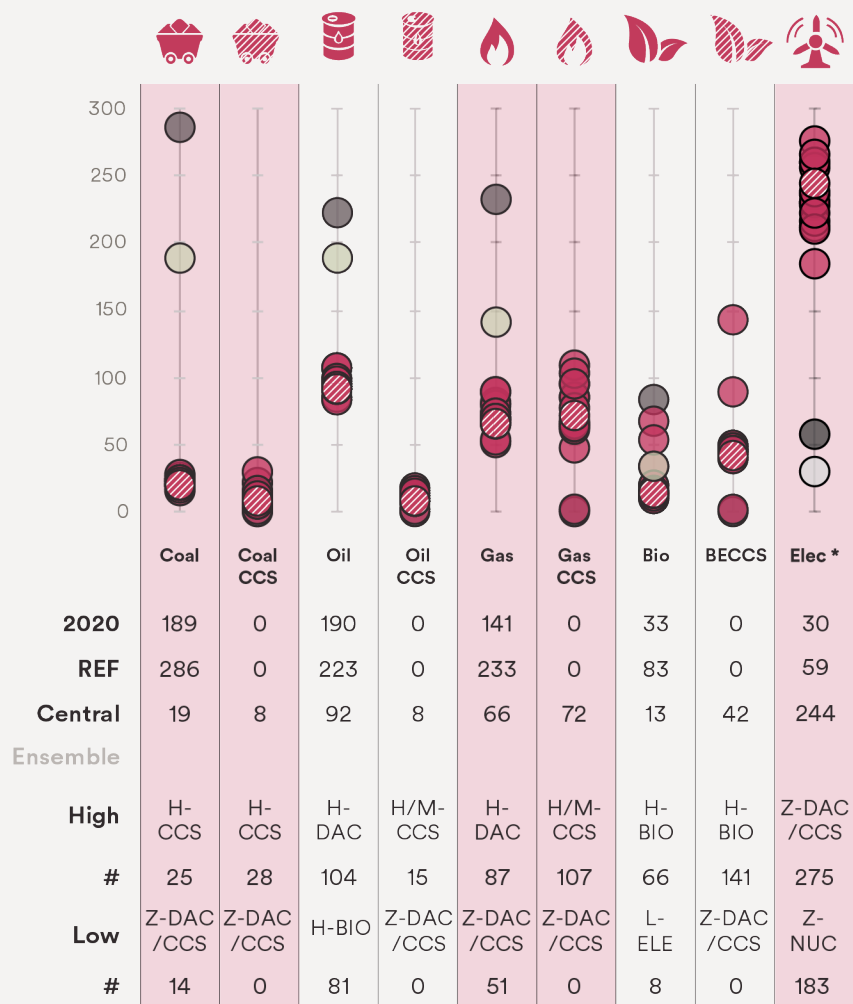
c. The graph shows the change in the generation mix of fuel demand from 2015 to 2050. The Reference total is shown by the dark striped line. In comparison, the Central scenario has 44% less demand than the Reference case by 2050. The scatter plot on the right presents an additional view of the 2050 values for the Ensemble results as well as the 2020 and 2050 Reference case points.

d. This shows 2050 final energy demand by fuel type across the Ensemble as well as a comparison with the Reference case and the 2020 values. The table highlights the highest and lowest scenario with its value across the ensemble.

*Elec represents all renewable energy plus nuclear energy.

● 2050 REF ● 2020 REF ● Central ● Ensemble

d. 2050 final energy Ensemble results (EJ)



Industry

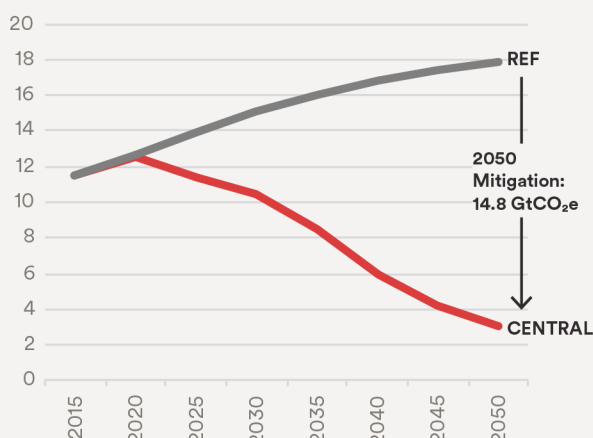
In 2020 the industrial sector produced roughly 13 GtCO₂e of direct and process-related emissions, or just under 23% of total emissions. In a Reference case, this sector is projected to reach nearly 18 GtCO₂e by 2050. Many of these emissions are from burning coal, gas, and oil for energy and heat in industrial, chemical, and metallurgical processes. Indirect emissions from electricity and fuel supply add roughly 9 GtCO₂e for a total of 22 GtCO₂e, equivalent to roughly 40% of total emissions in 2020.

Most of the mitigation in this sector comes from the catch-all category “other” industry (44%), iron and steel (24%), cement (17%), and chemicals (5%). Mitigation levers include improved efficiency, fuel switching (especially electrification), and demand reduction measures through materials substitution and the mass adoption of circular economy approaches. By 2030 the Central scenario achieves a 31% decrease from a Reference case, which is an 18% decrease in direct emissions compared with 2020 owing to a diffuse deployment of interventions. By 2050 the Central scenario reduces direct emissions by around 15 GtCO₂e in comparison with this Reference case, with residual emissions (those emissions remaining that require balancing out with CDR to achieve net zero) of 3.4 GtCO₂e (~74% reduction relative to 2020). This is the second-largest category of residual emissions after agriculture.

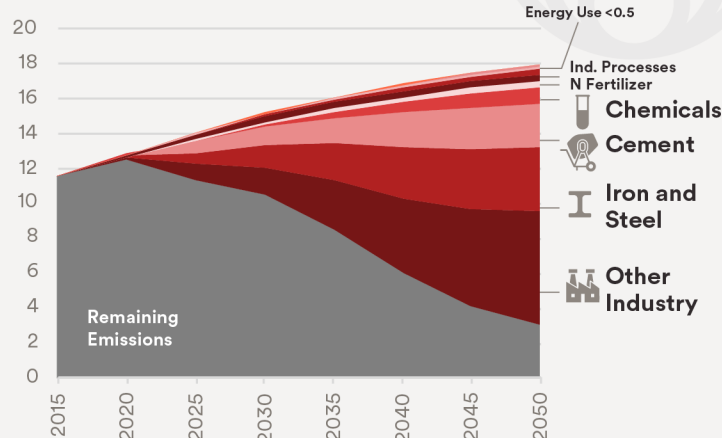


FIGURE 14: INDUSTRY SECTOR

Global industry emissions (GtCO₂e/yr)



Mitigation by end use (GtCO₂e/yr)



2050 total mitigation by region (GtCO₂e)

	Global	Africa	Asia (RO) and Oceania	Brazil	C Asia, M East, Russia	China	Europe	India	Latin America (RO)	SE Asia	U.S.A. & Canada
Other industry	6.5	0.5	0.3	0.1	0.9	2.0	0.4	0.9	0.3	0.6	0.4
Iron and steel	3.6	0.1	0.1	0.1	0.2	1.1	0.2	1.7	0.1	0.0	0.1
Cement	2.5	0.2	0.1	0.0	0.3	0.9	0.2	0.4	0.1	0.2	0.1
Chemicals	1.0	0.0	0.1	0.0	0.2	0.3	0.1	0.0	0.0	0.1	0.2
N fertilizer	0.4	0.1	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0
Industrial processes	0.3	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0
Ag. energy use	0.3	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0
Extractive Industries	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Construction	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Aluminum	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Cross-Sectoral											
Non-CO ₂	0.6	0.2	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0
TOTAL	14.8	1.0	0.6	0.2	1.7	4.7	1.1	3.1	0.5	1.0	0.9

In 2050, compared with a Reference scenario, the Central scenario reduces direct Industry emissions by around 14.8 Gt CO₂e. This is around 21% of total mitigation distributed across multiple subsectors. Totals might have a slight mismatch due to rounding.

Industry Ensemble results

The Ensemble scenario shows potential emissions reductions of 66% to 86% by 2050 for the industrial sector, relative to 2020 values. Residual emissions are as high as 4.3 GtCO₂e in the H-BIO scenario or as low as 1.8 GtCO₂e in the L-TEL scenario for a total range of around 2.5 Gt. In contrast, the Central scenario for this reduces to almost 3.1 GtCO₂e, or 76% compared with 2020.

In 2050 industrial emissions make up a sizable portion of residual emissions. This is due in part to perceived limitations on the amount of electrification, the deployment of CCS process emissions in cement and petrochemicals, and the remaining use of unabated fossil fuels either for heat or as industrial feedstocks. For final energy use in the industry sector, the Ensemble shows that electrification may reach 35% to 50%, CCS (combining all fossil fuels) is between 10% and 22%, unabated fossil fuel use is 30% to 45%, and the remaining 2% to 10% is the use of bioenergy. These are significant changes in comparison with 2020, where unabated fossil fuel use stands at above 70% and electricity is at around 18%, with the remainder bioenergy and cogeneration. Regardless of the pathway, direct coal use is significantly reduced from a peak of around 30% in 2020 to around 6% by 2050 (with 2% being unabated and 4% using CCS).

An update within the GCAM model is a downscaling of data to more specific industrial sectors, as seen in Figure 15 in the Sankey diagram that outlines 2020 emissions, with additional details in the Technical Summary. These data reveal significant variations in the starting and ending points in terms of electrification, the use of efficiency, and the deployment of CCS. Some industries, like aluminum manufacturing, are already highly electrified compared with other heavy and high-heat subsectors such as cement, chemicals, and iron and steel.

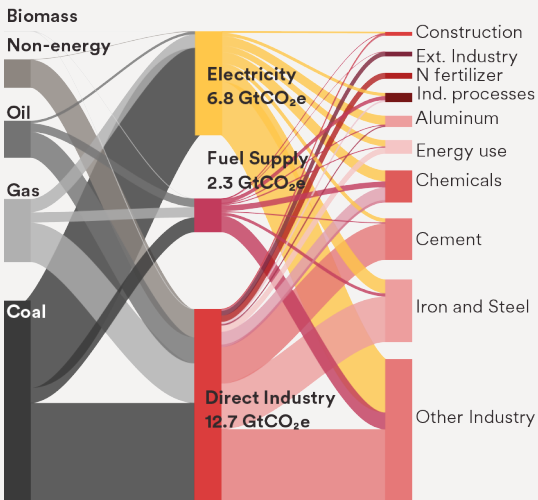
Industrial sector: insights and pathway implications

The industrial sector is highly varied, ranging from large, heavy industries like iron and steel and cement to small-scale manufacturing. There are mitigation opportunities common to all, but unlike sectors such as electricity, which is far more concentrated (in large or national grids) and regulated (by public utility commissions or departments), the industrial sector and its related policy environment is often dispersed, complex, and regionally specific. Because of this, mitigation efforts have focused on economy-wide application of carbon pricing mechanisms. While there are examples where such mechanisms are succeeding, there are also failures for pricing to reach adequate amounts or to be passed by legislative bodies, as is the case in the United States at the federal level today.

As a result, recent climate change mitigation strategies in the industrial sector take a broader, more innovative approach. These include “buy clean” initiatives that focus on demand-side procurement guidelines, carbon border adjustment taxes, incentives for productivity and efficiency, incentives for fuel switching including electrification and the use of alternate fuels for high-heat applications, and corporate emissions accountability. Together these measures work to help decarbonize production methods and can prepare the ground for stronger regulations.

FIGURE 15: INDUSTRY SECTOR DASHBOARD

a. Industry emissions flows (21.8 2020 GtCO₂e of associated emissions)



a. This figure shows the flow from direct source to upstream emissions (electricity and fuel supply) and final emissions, and finally splitting into industrial end uses. For an in-depth view of this Sankey flow as well as detailed amounts of emissions, please refer to the Technical Summary (TS Table 4).

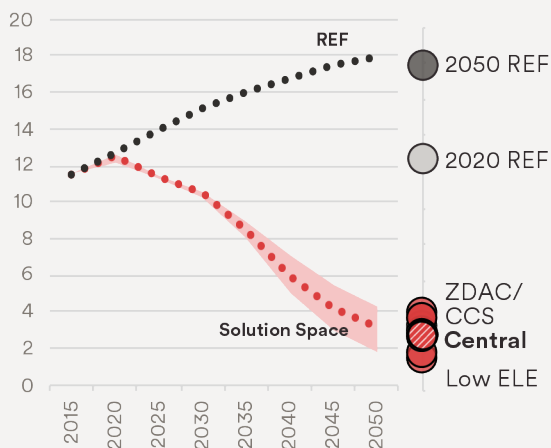
b. The gray dotted line displays the Reference case and the red line displays the Central scenario. The red-shaded area represents the range of values for the full Ensemble. The scatter plot at the right takes the 2050 values of this graph displaying the Ensemble and Central scenarios and Reference case for 2020 and 2050.

c. The graph shows the change of final energy demand for industry from 2015 to 2050. The Reference case is shown in the dark striped line. In comparison, the Central scenario has 18% less demand than the Reference case by 2050. The scatter plot on the right presents an additional view of the 2050 values of this graph as well as the 2020 Reference case point.

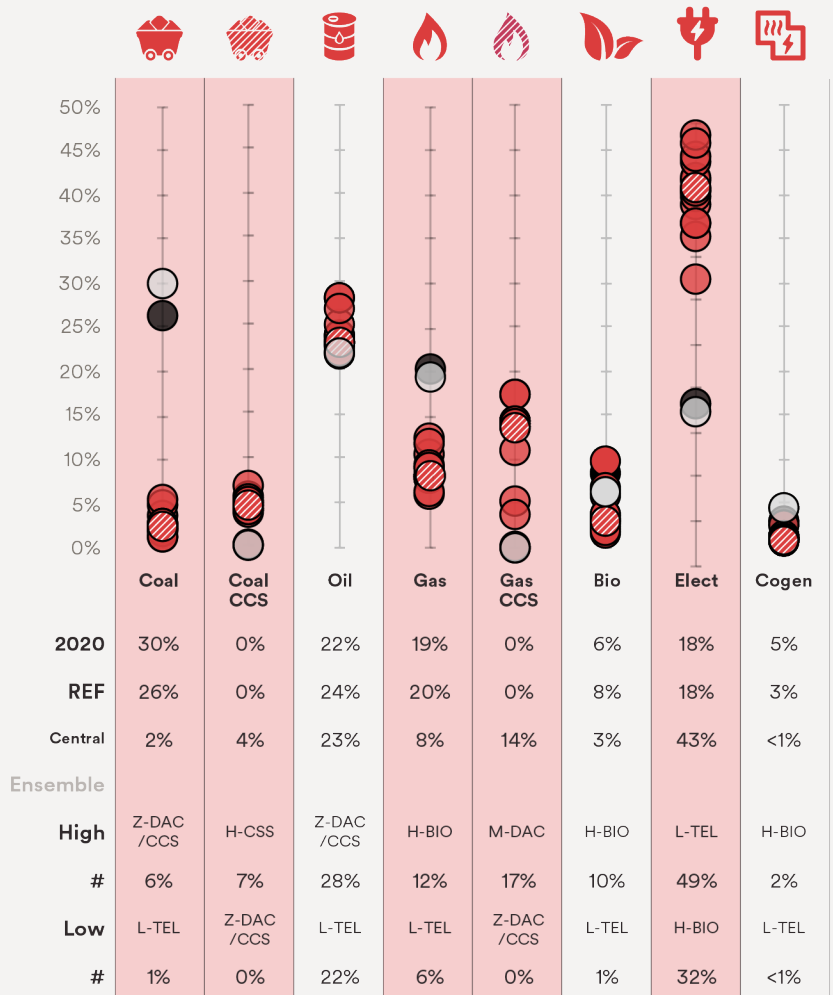
d. This shows 2050 final energy demand for select sources across the ensemble as well as comparison with the Reference case and the 2020 values. The table highlights the highest and lowest scenario with its value across the Ensemble showing variation based on scenario narrative.

● 2050 REF ● 2020 REF ● Central ● Ensemble

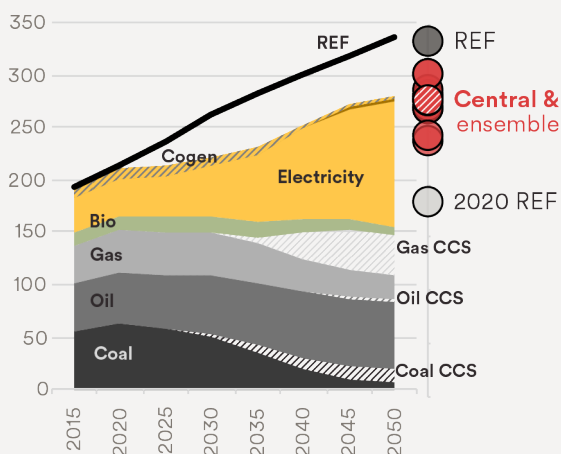
b. 2015-2050 direct and process industry emissions (GtCO₂e/yr)



d. 2050 Ensemble results for industry energy (Share of final energy demand by select sources)



c. Industry final energy demand (EJ)



Buildings

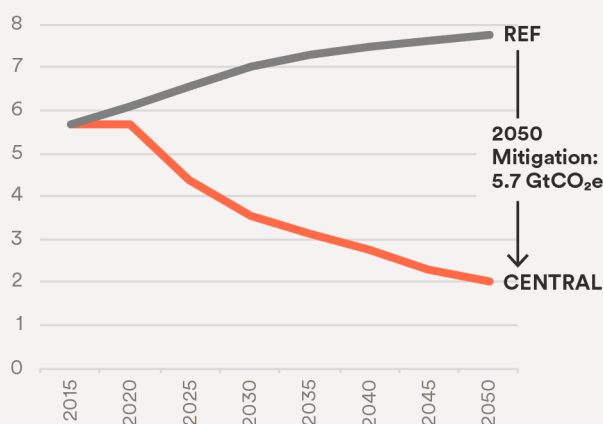
In 2020 buildings accounted for around 6 GtCO₂e, or roughly 11% of total global emissions. This includes not only direct fuel use within homes and businesses but also the associated nonenergy emissions like fluorinated gases (F-gases) and waste-related emissions (MWS and wastewater). We include the latter category of emissions within the buildings sector to represent a wider view of our built environment. Indirect emissions from electricity and fuel supply add 8 GtCO₂e to this sector for a total of 14 GtCO₂e, or roughly 26% of total emissions in 2020. If current trends continue, this figure could rise to almost 8 GtCO₂e of direct emissions by 2050, or 22.6 GtCO₂e when indirect emissions are included.

Achieving a 1.5° C pathway will require direct buildings emissions reductions of 41% by 2030 and 67% by 2050 relative to 2020 levels. Compared with a Reference case, direct emissions are reduced by 3.5 GtCO₂e and 5.7 GtCO₂e by 2030 and 2050, respectively, or around 8.2% of total mitigation by 2050. Nearly 40% of emissions reductions in this sector come from appliances, water, cooking, and cooling for residential use. Emissions reductions related to urban processes (waste) contribute an estimated 15% of this total. Cooling adds 14% of emissions reductions in the form of F-gas reductions (other, related reductions are indirect and assigned to the electricity sector). And finally, residential, and commercial heating makes up 20% of reductions. Electrification plays a large role in this sector as heating systems and appliances like water heaters, stoves, and clothes dryers transition from direct on-site combustion to electric devices. Super pollutants, in the form of methane associated with waste and F-gases associated with cooling and refrigeration, make up a large share of these reductions. Indirect or fuel-supply-related emissions account for a total of nearly 16 GtCO₂e in additional reductions.

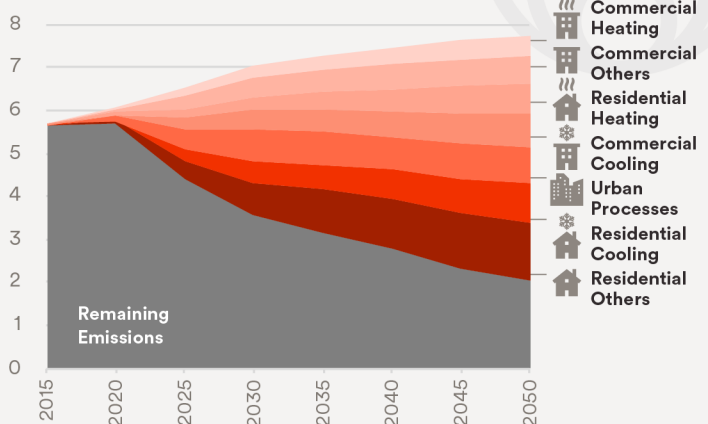


FIGURE 16: BUILDINGS SECTOR

Global buildings emissions (GtCO₂e/yr)



Mitigation by end use (GtCO₂e/yr)



2050 total mitigation by region (GtCO₂e)

	Global	Africa	Asia (RO) and Oceania	Brazil	C Asia, M East, Russia	China	Europe	India	Latin America (RO)	SE Asia	U.S.A. & Canada
Comm cooling	0.8	0.1	0.0	0.0	0.1	0.2	0.0	0.1	0.0	0.1	0.0
Resid cooling	0.9	0.1	0.0	0.0	0.2	0.2	0.0	0.1	0.0	0.2	0.0
Comm heating	0.4	0.0	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.0	0.1
Comm others	0.6	0.1	0.0	0.0	0.1	0.1	0.1	0.1	0.0	0.0	0.1
Resid heating	0.7	0.0	0.1	0.0	0.1	0.2	0.2	0.0	0.0	0.0	0.2
Resid others	1.4	0.1	0.2	0.0	0.2	0.3	0.2	0.1	0.1	0.1	0.1
Urban processes	0.9	0.1	0.0	0.0	0.2	0.1	0.1	0.0	0.1	0.1	0.0
Cross-Sectoral											
Non-CO ₂	2.8	0.3	0.3	0.1	0.5	0.5	0.2	0.2	0.2	0.4	0.1
TOTAL	5.7	0.5	0.4	0.1	0.9	1.2	0.8	0.4	0.3	0.5	0.6

In 2050 compared with a Reference scenario, the Central scenario reduces direct Buildings-related emissions by around 5.7 Gt CO₂e. This is around 8% of total mitigation distributed across multiple subsectors. Note that this includes end uses as well as waste (Urban Processes) representing emissions from the larger built environment. Totals might have a slight mismatch due to rounding.

Buildings Ensemble results

The buildings sector refers to the broad built environment and the communities in which people live, work, and thrive, and it involves how people interact with energy, devices, and services in their everyday lives. By 2050 buildings emissions in the Central scenario are reduced to around 2 GtCO₂e, but the Ensemble scenarios add plus or minus ~0.5 GtCO₂e for a range of about 1 GtCO₂e. Both the Low and Medium Electrification scenarios achieve the largest emissions reductions by 2050, as the underlying scenario narrative focuses on transport electrification. If transportation electrification fails, those emissions must be reduced elsewhere, and the model sees opportunities in buildings as a viable cost-effective option. Conversely, in the M-DAC and H-DAC scenarios, the model allows buildings more emissions due to higher levels of CDR.

With a decarbonized grid, electrification and efficiency are key to reducing emissions in buildings. This is seen in the Central scenario as electrified shares of energy use in buildings rise from 36% in 2020 to 82% by 2050. Total final energy is reduced by 23% in comparison with a Reference case. Many of these efficiency gains are from heating and from “other” subsectors, a category that includes plug loads for appliances, water heating, and lighting.

Expanded access to clean cooling can mask simultaneous gains in efficiency. Therefore, we see similar energy requirements for both the Reference case and the Central/Ensemble results, and yet cooling demand rises further than a Reference case and more than doubles in the Central/Ensemble scenarios relative to 2020. This demand growth is offset by around 30% in efficiency gains. Cooling technology also reduces non-energy-related emissions by moving away from the use of F-gases.

Together, total energy consumption across end uses in buildings rises across all Ensemble scenarios by 9% to 18% — but far less than the 46% rise in a Reference case. As in other sectors, the extent of possible total energy reductions is a matter of active debate. The Ensemble consistently emphasizes equitable access to energy and cooling, resulting in higher energy demand than in other low-energy-demand scenarios. This higher energy demands represent higher access to service provisions, a necessary component of how we model equitable access.

Buildings sector: insights and pathway implications

There are many actors in the buildings sector, and factors in mitigation efforts include both individual consumption patterns and how communities, housing, and workplaces are organized, are built, and interact with surrounding ecosystems. As with other sectors, there are push and pull measures that regulate or incentivize a variety of decarbonization approaches, ranging from simple efficiency standards and labeling to more complex urban design strategies that leverage energy and transport networks alongside buildings.

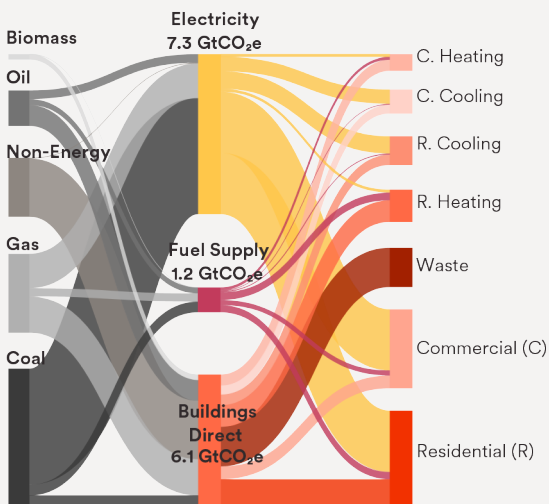
Broadly, push measures include buildings codes and appliance standards that ratchet up efficiency and change fuel consumption patterns toward electrified sources, thus taking full advantage of a decarbonizing grid. Such measures, however, must be balanced with pull measures that lower costs, shrink administrative barriers, and provide incentives for comprehensive upgrades to equipment and appliances, retrofits of building stocks, and the design and construction of more climate-friendly and climate-resilient buildings. Further research is needed to link such measures to equity considerations that recognize energy burden, energy access, limited resources, economic development, and historical inequities.



Buildings

FIGURE 17: BUILDINGS SECTOR DASHBOARD

a. 2020 buildings emissions flows (14.5 GtCO₂e of associated emissions)



a. This figure shows the flow from direct source to up/midstream emissions (electricity and fuel supply) and final emissions in buildings, and finally splits into end uses. For an in-depth view of this Sankey flow as well as detailed amounts of emissions, please refer to the Technical Summary (TS Table 4).

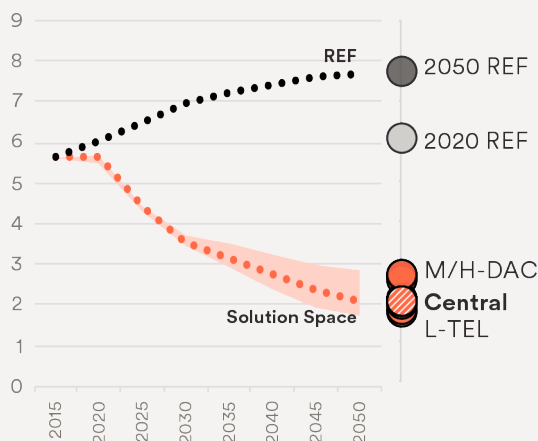
b. The gray dotted line displays the Reference case and the orange line displays the Central scenario. The orange-shaded area represents the range of values for the full GCAM-CWF Ensemble. The scatter plot on the right takes the 2050 values of this graph displaying the Ensemble and Central scenarios and Reference case for 2020 and 2050.

c. The graph shows the change in final energy demand for buildings from 2015 to 2050. The Reference case is shown in the dark line. In comparison, the Central scenario has 26% less demand than the Reference case by 2050. The scatter plot on the right presents an additional view of the 2050 values for the Ensemble, as well as the 2020 Reference case point.

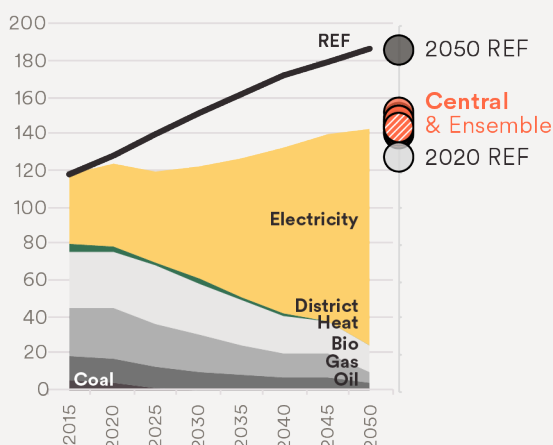
d. This shows the 2050 energy demand for end uses and the shares for that end use that is electrified across the Ensemble as well as a comparison with the Reference case and the 2020 values. The table highlights the highest and lowest scenario with its value across the Ensemble showing variation based on scenario narrative.

● 2050 REF ● 2020 REF ● Central ● Ensemble

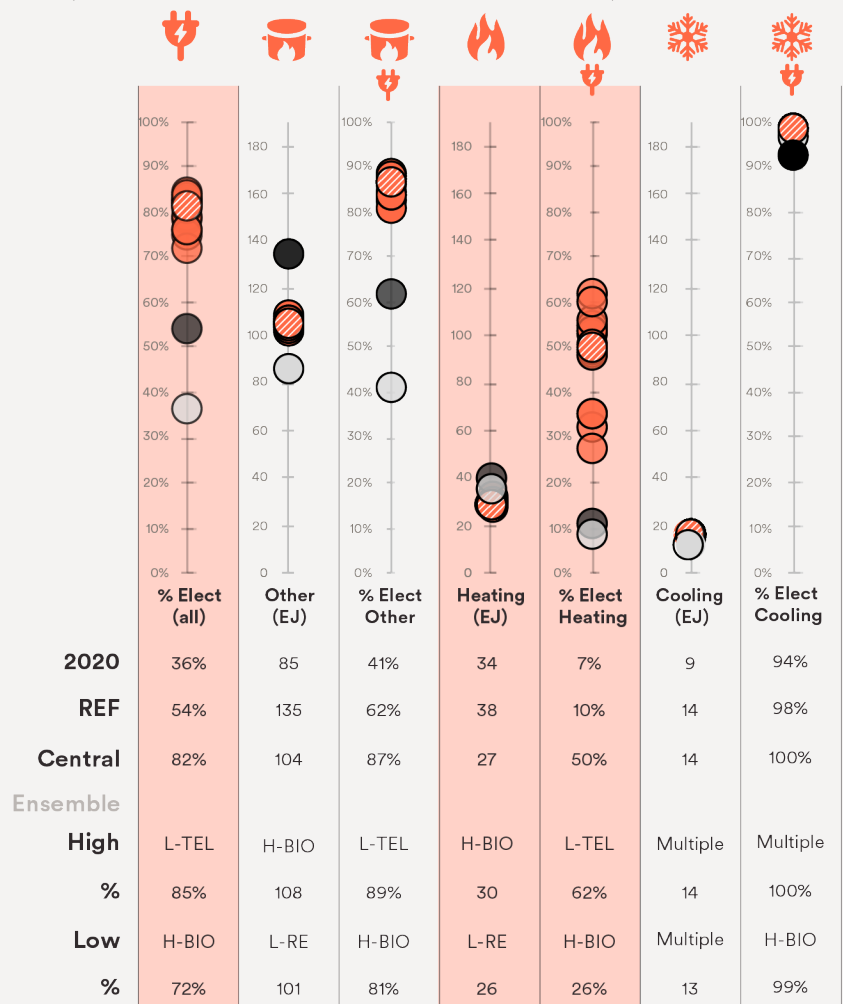
b. 2015-2050 direct buildings emissions (GtCO₂e/yr)



c. Final energy demand by source (EJ)



d. 2050 Ensemble energy and share electric (Share electric and direct on-site fuel for end use)



Transport

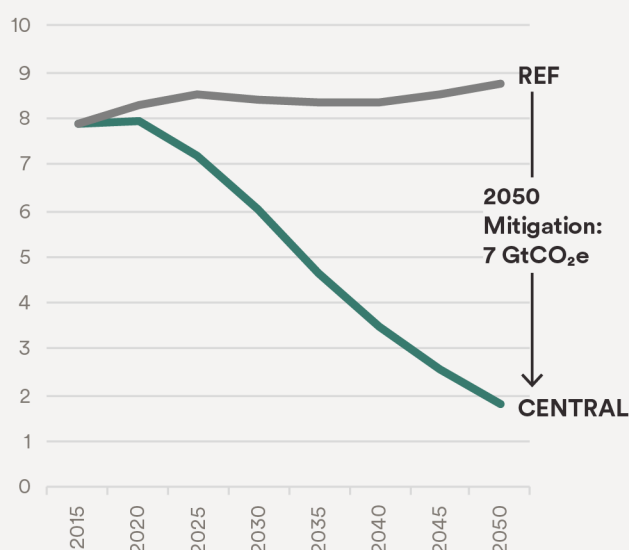
In 2020 direct tailpipe emissions from transport represented around 8 GtCO₂e, or nearly 15% of total emissions. This number increases to just under 10 GtCO₂e when indirect emissions from electricity and fuel supply are added, for a total share of roughly 18%. Following the current trend, direct and indirect emissions in transport could reach above 11 GtCO₂e by 2050. Roughly 76% of transport emissions are related to land-based passenger and freight road transport. Emissions from aviation and shipping account for the remaining 24% of 2020 emissions. Efficiency and fuel switching, including electrification, allow scaled emissions mitigation in the Central scenario, and sustained action will be needed to ensure that by 2030 emissions are reduced by roughly 27% from 2020 levels. Reductions must reach nearly 78% by 2050.

When indirect emissions are included, transportation provides the opportunity to eliminate around 9.4 GtCO₂e of emissions by 2050 (7 GtCO₂e direct and 2.4 GtCO₂e indirect), or around 13% of total mitigation. Indirect and fuel-supply-related emissions are discussed further in the next section.

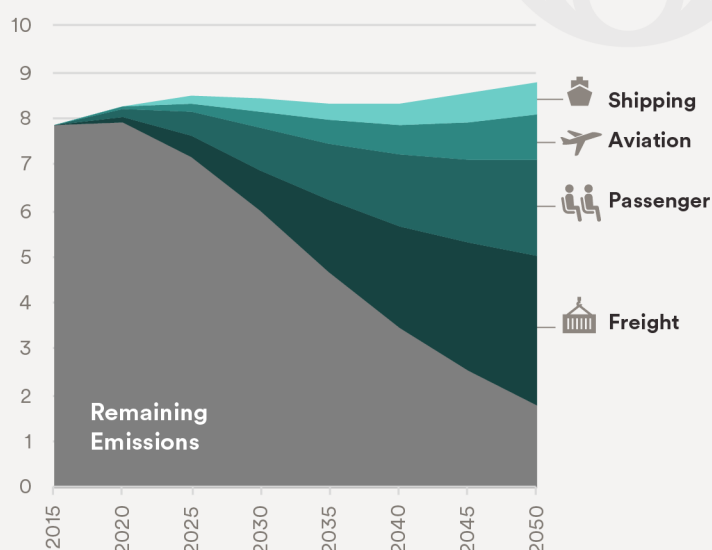


FIGURE 18: TRANSPORT SECTOR

Global transport emissions (GtCO₂e/yr)



Mitigation by end use (GtCO₂e/yr)



2050 total mitigation by region (GtCO₂e)

	Global	Africa	Asia (RO) and Oceania	Brazil	C Asia, M East, Russia	China	Europe	India	Latin America (RO)	Southeast Asia	U.S.A. & Canada
Shipping	0.7	0.0	0.1	0.0	0.1	0.2	0.1	0.0	0.0	0.1	0.1
Aviation	1.0	0.1	0.0	0.0	0.1	0.2	0.1	0.1	0.0	0.1	0.1
Passenger	2.1	0.3	0.1	0.0	0.3	0.2	0.4	0.1	0.1	0.1	0.5
Freight	3.2	0.3	0.2	0.1	0.3	0.8	0.2	0.3	0.2	0.2	0.6
Cross-Sectoral											
Non-CO ₂	0.2	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
TOTAL	7.0	0.7	0.4	0.2	0.8	1.3	0.8	0.6	0.4	0.6	1.3

In 2050, compared with a Reference scenario, the Central scenario reduces direct Transportation-related emissions by around 7 Gt CO₂e. This is around 10% of total mitigation distributed across multiple subsectors. Totals might have a slight mismatch due to rounding.

Transport Ensemble results

In the transport sector, there is a range of 2.3 GtCO₂e between the highest and lowest emissions scenarios in the Ensemble by 2050. The scenario with the highest emissions is L-TEL, with 3.9 GtCO₂e by 2050, followed by M-TEL, with 3.4 GtCO₂e. The Zero DAC/CCS scenario is the most ambitious, with nearly 80% in emissions reductions compared with current levels, leaving only 1.6 GtCO₂e by 2050. The Central scenario is slightly lower than the Ensemble's mean, and it reduces by around 1 GtCO₂e every decade, reaching 1.8 GtCO₂e by 2050. This Central scenario aligns very closely with much of the rest of the Ensemble scenarios, all of which utilize high rates of electrification.

More so than other end-use sectors, transport energy use can be reduced significantly by midcentury through electrification. Electric vehicles are three to five times more efficient than conventional vehicles, which results in significantly lower total energy use. By 2050, total final energy decreases by around 50% from 2020 levels and by roughly 60% compared with a Reference case. Accomplishing this will require fully electrifying all new vehicles by 2050, as envisioned in the Central scenario, and shifting toward shared and public options. Around 90% of the total distance traveled by passenger and freight vehicles is electrified by 2050, with the remaining 10% split among oil, biofuels, and gas. In energy terms, these remaining combustion vehicles take up larger shares of energy (at around 14% each) due to their inefficiencies. Within the Ensemble, two pathways, L-TEL and M-TEL, can help evaluate slower electrification. Each has higher emissions, with an additional 1.6 GtCO₂e and 1.9 GtCO₂e, respectively, in 2050. These scenarios still achieve net-zero emissions by 2050, which indicates that reductions must be made elsewhere, either in other sectors or through carbon dioxide removal.

Meanwhile, there are fewer options in the shipping and aviation subsectors in the current modeling structure. Options include the use of more efficient motors, the use of biofuels, and demand reductions that achieve a flatlining of emissions, keeping them roughly at 2020 levels. While this represents a large reduction compared with a Reference case, they remain a significant share of residual emissions by 2050. However, there are alternative fuels now under exploration, including hydrogen, ammonia, and synthetic and electro-fuels. While early research is promising, these fuels also come with potential trade-offs worth considering, including high estimated costs, competition for use in other sectors (most importantly in fertilizers), and potentially deleterious effects through emissions leakage.¹⁴

Transport sector: insights and pathway implications

While the transportation of people and goods is fundamental to economies and livelihoods, the use of petroleum-based fuels currently dominates this sector. Fortunately, advances in battery technologies and alternative low- and zero-carbon fuels are generating revolutionary opportunities to fully decarbonize the road, freight, shipping, and aviation sectors. Strong measures are needed to scale these alternative fuels for impact and to shift people toward the use of more sustainable modes of transportation like walking, biking, and public transit and away from energy-intensive modes that drive more emissions.

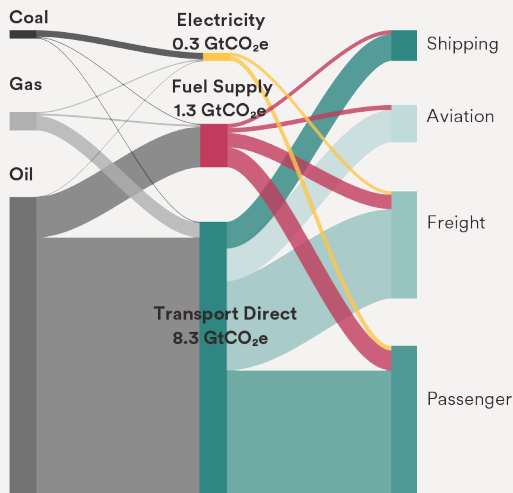
Already there are ambitious efforts underway to phase out emissions-intensive modes of transportation. These include regulatory frameworks that establish timelines to end the sale of internal combustion engines and financial incentives that aim to scale investments in alternative fuel development, efficient vehicles and fleets, and the buildout of necessary infrastructure. When implemented successfully, these measures reduce greenhouse gas emissions and local pollutants, contributing to healthier communities. Additionally, the growing availability of alternative fuels means that these sectors can decarbonize faster, alleviating stress on an oversubscribed carbon budget. This is demonstrated by evaluating the L-TEL and M-TEL scenarios in comparison with the Central scenario. With a finite carbon budget, faster and deeper decarbonization of the transport sector provides space for other sectors to transition gradually while remaining consistent with a 1.5° C pathway.



Transport

FIGURE 19: TRANSPORT SECTOR DASHBOARD

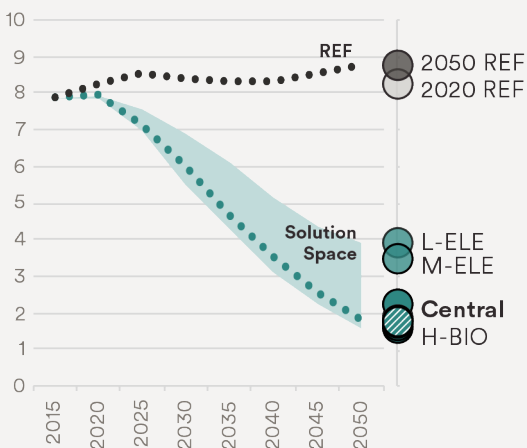
a. 2020 transport emissions flows (9.9 GtCO₂e of associated emissions)



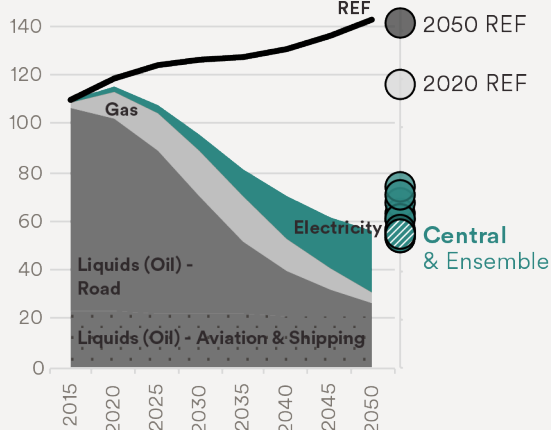
- a. This figure shows the flow from direct source to up/midstream emissions (electricity and fuel supply) and final emissions in transport, and finally splits into end uses. For an in-depth view of this Sankey flow as well as detailed amounts of emissions, please refer to the Technical Summary (TS Table 5).
- b. The gray dotted line displays the Reference case and the teal line displays the Central scenario. The teal-shaded area represents the range of values for the full Ensemble. The scatter plot on the right takes the 2050 values of this graph displaying the Ensemble and Central scenarios and Reference case for 2020 and 2050.
- c. The graph shows the change in energy sources from 2015 to 2050. The Reference case is shown in the dark line. In comparison, the Central scenario has 72% less demand than the Reference case by 2050. The scatter plot on the right presents an additional view of the 2050 values for the Ensemble, as well as the 2020 Reference case point.
- d. This shows the 2050 shares by energy type (for all transport and then the share of electrification for road) across the Ensemble as well as a comparison with the Reference case and the 2020 values. The table highlights the highest and lowest scenario with its value across the Ensemble showing variation based on scenario narrative.

● 2050 REF ● 2020 REF ● Central ● Ensemble

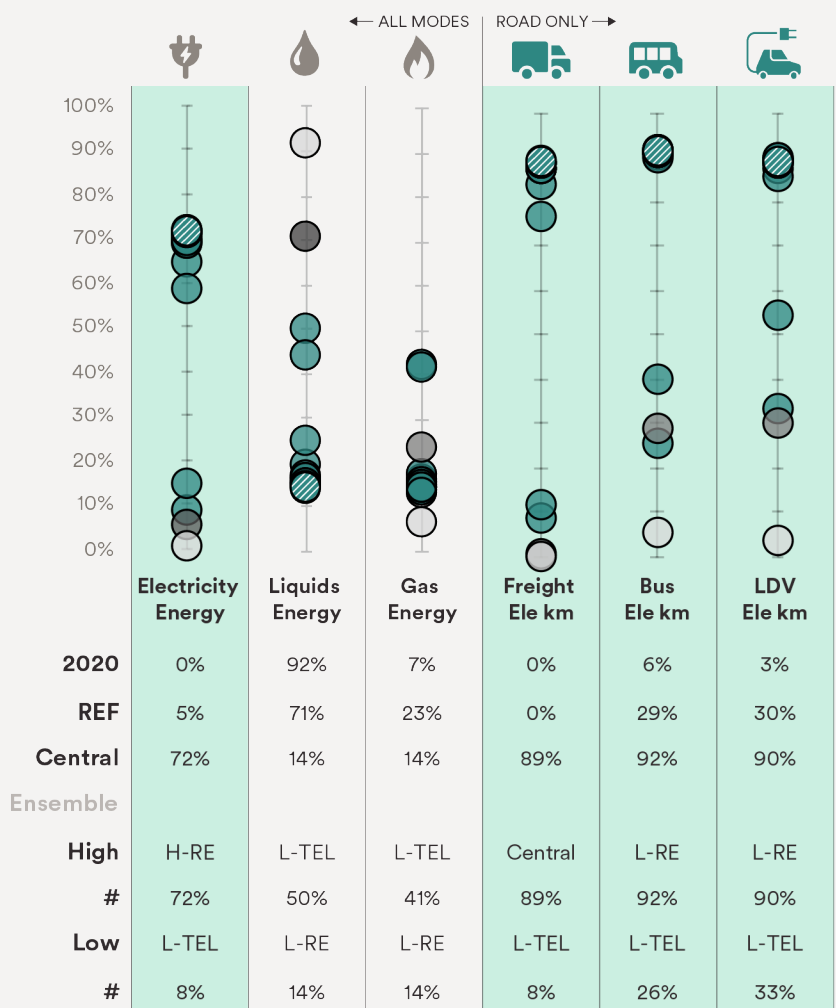
b. 2015-2050 direct transport emissions (GtCO₂e/yr)



c. Energy by source (EJ/yr)



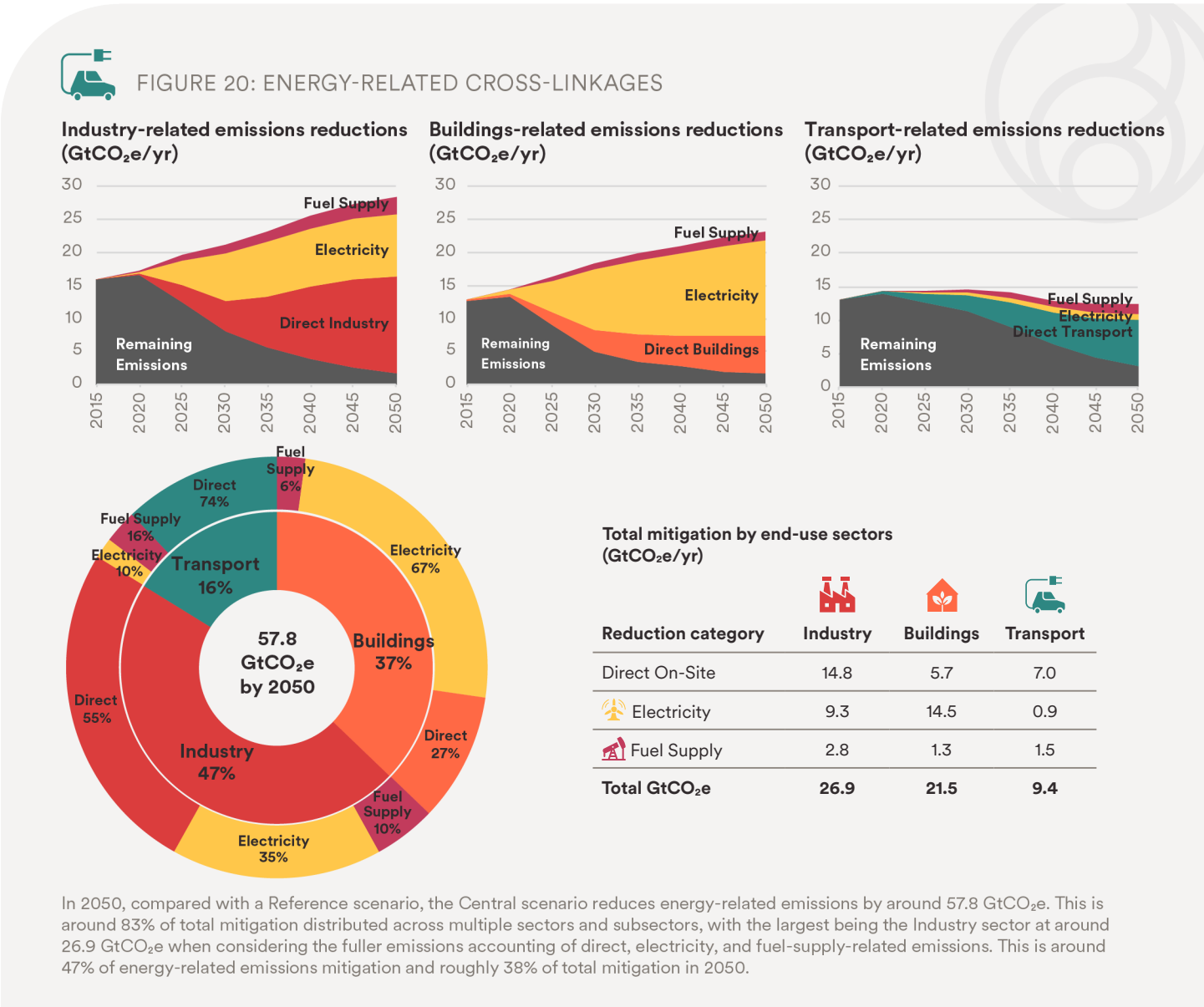
d. 2050 energy shares for Ensemble scenarios (Share by fuel for all modes, and share electrified road)



Energy-related linkages

The GCAM-CWF scenario envisions a large transition of the global energy system toward more sustainable energy deployment, including widespread deployment of efficiency measures and electrification across end uses. Figure 20 deconstructs emissions reductions at the global level for each of the three end-use sectors of industry, buildings, and transport as they relate to the energy supply sectors (electricity and fuel supply). This highlights the need for a full systems approach to the transformation of emissions across categories of direct (on-site) emissions, fuel supply (upstream and midstream emissions related to fuel supply extraction, processing, and distribution), and indirect emissions related to generation of electricity.

For example, space heating, when switching fuels from coal or natural gas to electrified sources, achieves deeper emissions reductions if the electricity used is generated from net-zero emissions technologies. The use of electric arc furnaces in industry achieves the same end as the use of battery electric vehicles across modes within the transportation sector. Relatedly, as these sectors electrify, demand for fuels is reduced so that emissions associated with the extraction and processing of fuels (see the section on fuel supply, above) are simultaneously reduced. Only by taking an integrated systems approach to mitigation can the full spectrum of reductions become apparent due to the interplay of supply and end-use demand sectors.



Agriculture

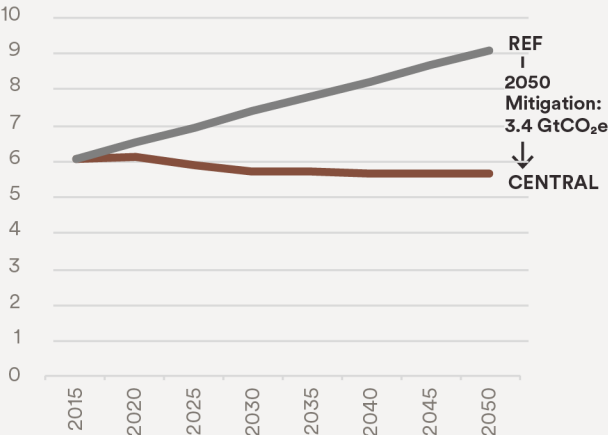
For the agriculture sector, we focus on a large subset of direct emissions as those associated with food production from farms, ranches, and other operations that grow food, feed, fiber, and fuel. This definition excludes emissions from food waste and energy and industrial emissions components of the production of mechanized equipment, fertilizer production, processing, and transport, which are reported in industrial, transport, and power sectors. Land-related emissions, reductions, and sinks, which overlap significantly with agriculture, are discussed in the next section on forests and land use. Direct emissions from agriculture generated more than 6 GtCO₂e in 2020, or 12% of the total of Global emissions. (Note that estimates taking into account both direct and wider food and agricultural systems emissions from other sectors total around one-third of emissions.)¹⁵ These emissions were mainly methane associated with meat and dairy production (55%) and cultivation of certain crops, like rice.

Following the Reference scenario, emissions from agriculture could reach around 9 GtCO₂e by 2050. Most of this growth would come from increased demand for meat and dairy products as populations and economies grow. Conversely, changes in agricultural practices and production intensification could lower emissions by 3.4 GtCO₂e by 2050 compared with the Reference case (or 5% of total mitigation) when coupled with dietary shifts away from meat and dairy. In the Central scenario, emissions from agriculture account for 5.6 GtCO₂e in 2050. This is the largest single category of residual emissions. However, the intensification of crop production and the reduced need for pastureland would free up land needed for natural carbon dioxide removal and bioenergy, as seen in the next section.

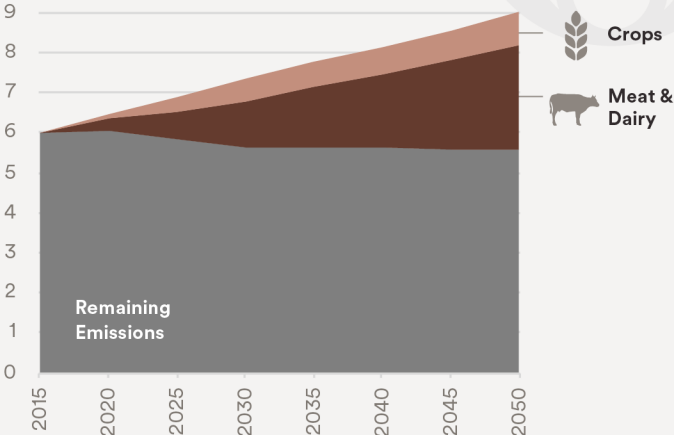


FIGURE 21: AGRICULTURE SECTOR

Global agricultural emissions (GtCO₂e/yr)



Mitigation by end use (GtCO₂e/yr)



2050 total mitigation by region (GtCO₂e)

	Global	Africa	Asia (RO) and Oceania	Brazil	C Asia, M East, Russia	China	Europe	India	Latin America (RO)	SE Asia	U.S.A. & Canada
Crops (Non-CO ₂)	0.8	0.3	0.0	0.1	0.0	0.1	0.0	0.0	0.1	0.1	0.0
Meat & Dairy (Non-CO ₂)	2.6	0.9	0.2	0.2	0.2	0.3	0.1	0.2	0.2	0.1	0.2
Cross-Sectoral											
Non-CO ₂	3.4	1.1	0.2	0.2	0.3	0.4	0.2	0.3	0.2	0.2	0.2
TOTAL	3.4	1.1	0.2	0.2	0.3	0.4	0.2	0.3	0.2	0.2	0.2

In 2050, compared with a Reference scenario, the Central scenario reduces direct Agriculture-related emissions by around 3.4 GtCO₂e. This is around 5% of total mitigation distributed across multiple subsectors. This represents only so-called farm gate emissions or those directly associated with the production of food and does not include carbon fluxes related to land-use transition emissions or wider systems emissions associated with food processing, distribution, or waste. Totals might have a slight mismatch due to rounding.

Agriculture Ensemble results

In agriculture, the Ensemble scenarios are closely aligned, with a total difference of only 0.3 GtCO₂e by 2050 between the highest and lowest emissions scenarios. In all Ensemble scenarios, the greatest emissions reductions occur between 2020 and 2030. After 2030, emissions in agriculture continue to decrease, but at a slower rate, as productivity measures are offset by increased food demand related to growing affluence and population growth.

A combination of methods helps achieve agricultural emissions reductions, including improved production; shifting supply and demand to promote more consumption of low-emissions food and less consumption of emissions-intensive sources; a shift in land use toward climate-beneficial services; and reductions throughout the food system, including in transportation, processing, and waste streams. All these methods are used in the Central scenario. Relative to our study in 2020, this round of modeling sees fewer emissions reductions within the agricultural sector, but 3.4 GtCO₂e in annual on-farm emissions reductions by 2050 is still significant.¹⁶

Notably, interventions in this sector are interlinked with other sectors, especially land use. For example, emissions from cropland by 2050 drop by nearly 20% compared with 2020 levels, while enhanced productivity in agriculture helps meet the demands of growing affluence and population. Emissions from pastureland for grazing drop by around 32%.¹⁷ These later shifts occur through reducing demand for meat and changing feed practices. Land redistribution allows a focus on climate services like the dedicated production of bioenergy (including the use of crop residuals) and natural carbon dioxide removal on grasslands and in forests.

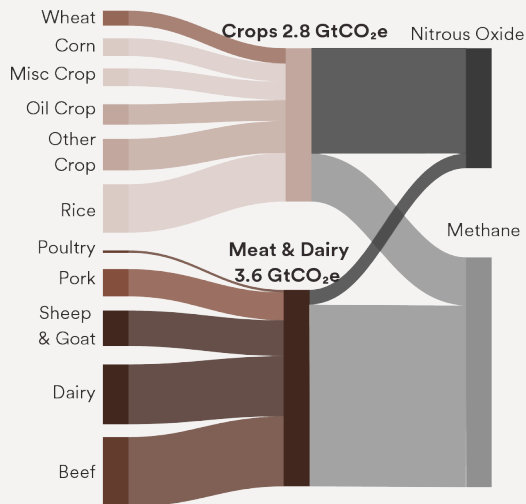
The Ensemble sees little difference across this sector as our current Low, Medium, and High approaches focus largely on energy sector interventions. We aim to better model our understanding of the opportunity space for food and agriculture in future analyses. This will potentially include both additional intervention points to shift direct agriculture emissions and synergies and trade-offs associated with reducing direct agricultural emissions alongside food-related emissions that occur in other sectors.

Agriculture: insights and pathway implications

Beyond measures to promote productivity, reduce pollution, and promote a shift to lower emissions products, there are opportunities to achieve additional emissions reductions by considering system approaches such as changes to distribution, processing, and cold chains and by limiting emissions from food waste. This involves overlap with other sectors (i.e., food processing in industry, transport of food, and energy consumption patterns in buildings). However, there is a need for additional research on shifts toward more sustainable practices that accounts for regional variations, customs, and equitable access.

FIGURE 22: AGRICULTURE SECTOR DASHBOARD

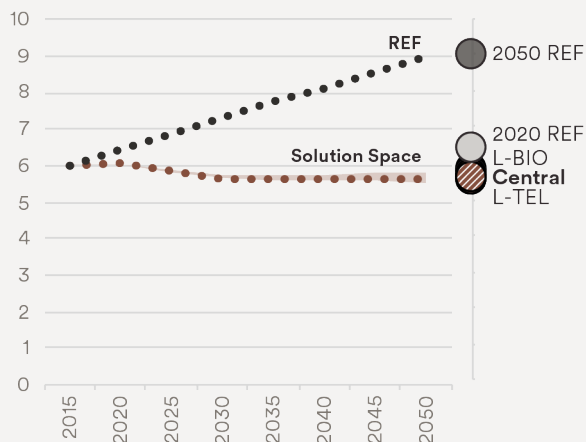
**a. 2020 agriculture emissions flows
(6.4 GtCO₂e of associated emissions)**



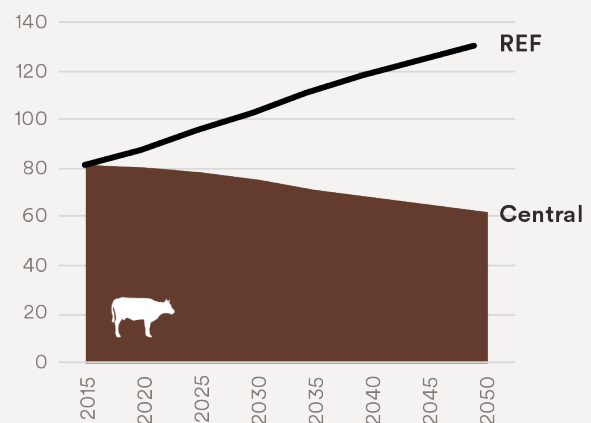
- a. This figure shows the flow from end uses to either crops or meat and dairy and finally to greenhouse gases. For a more detailed view, please refer to the Technical Summary (TS Table 5).
- b. The gray dotted line displays the Reference case and the brown line displays the Central scenario. The brown-shaded area represents the range of values for the full Ensemble. The scatter plot on the right takes the 2050 values of this graph displaying the Ensemble and Central scenarios and Reference case for 2020 and 2050.
- c. The graph shows the change in cropland from 2015 to 2050 in comparison with a Reference scenario. Wedges represent lands reallocated away from cropland, which is reduced by 22% from 2020 to 2050, giving space to pasture, bioenergy, forests, and grasslands.
- d. This graph represents the change in ruminant meat consumption (beef, sheep, and goat). The Reference case in the dark line shows a constant increase from 2015 to 2050, while the Central scenario decreases ruminant meat consumption by 26% in comparison with 2020.
- e. The line graphics reveal an increase in land productivity across crops from 2020 to 2050 as measured in the rate of change of Mt production per thousand km². The solid line represents the Central scenario while the dotted line represents the Reference scenario for the same selected crops.

● 2050 REF ● 2020 REF ● Central ● Ensemble

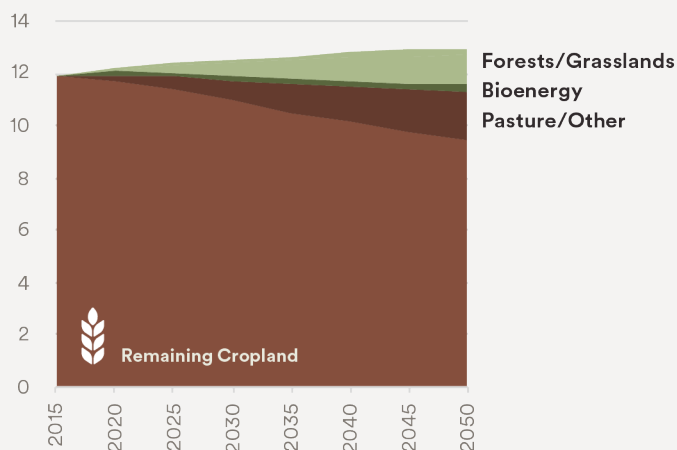
**b. 2015-2050 agriculture emissions
(GtCO₂e/yr)**



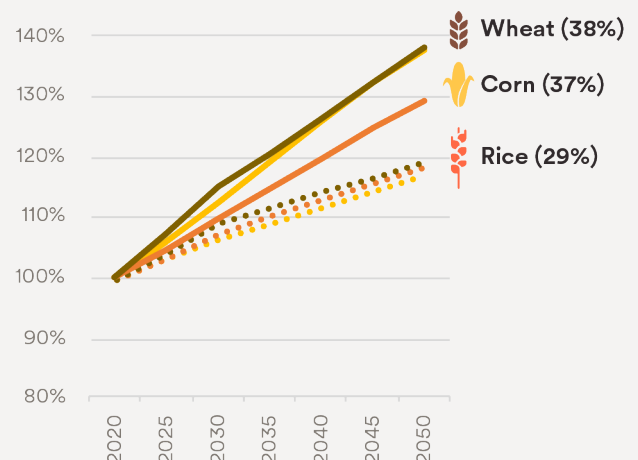
**d. Ruminant meat consumption
(Mt)**



**c. Cropland and reallocation
(mil km²)**



e. Land productivity for selected crops



Forest and land use

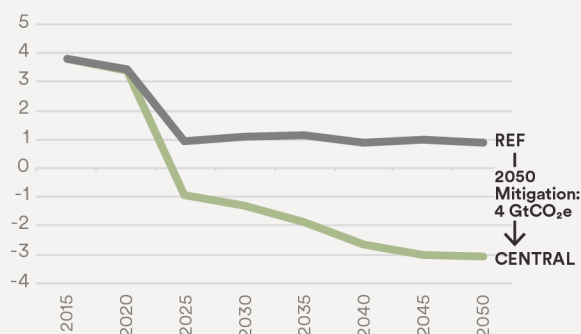
Carbon dioxide can be removed from the atmosphere and stored in forests and across other land types, offering a major climate service. At the same time, forest and land use can also be a source of GHGs — for example, through the conversion of primary forests to managed forests, deforestation, unsustainable forest management, and other land use changes. In total, forest and land use accounted for an estimated 3.4 GtCO₂e, or 6% of total emissions, in 2020.¹⁸

There is considerable uncertainty related to carbon fluxes (the amount of carbon exchanged annually between oceans, the atmosphere, and land) associated with forests and land use. And yet, there is agreement on the potential for land to become a substantial net carbon sink — that is, for annual carbon sequestration from land sources to outweigh yearly emissions. The Central scenario envisions a drop in emissions of 4.7 GtCO₂e by 2030 and 6.5 GtCO₂e by 2050, relative to 2020 numbers. This indicates that before 2030, forest and land use will sequester rather than emit CO₂, reaching around -1.3 GtCO₂e and -3 GtCO₂e by 2030 and 2050, respectively. However, this outcome will require concerted efforts to protect existing forest stocks (avoiding deforestation) while also promoting reforestation (restocking existing forests and woodland), afforestation (establishing forest cover in places that had none), and regenerative agricultural practices that promote carbon sequestration. Meanwhile, there will be increased competition for land, as there is a need to scale up agricultural production for growing populations and to produce bioenergy for use in select sectors (such as certain high-heat industrial sectors and shipping and aviation fueling). Overlaps with agricultural land use are significant and discussed further below.

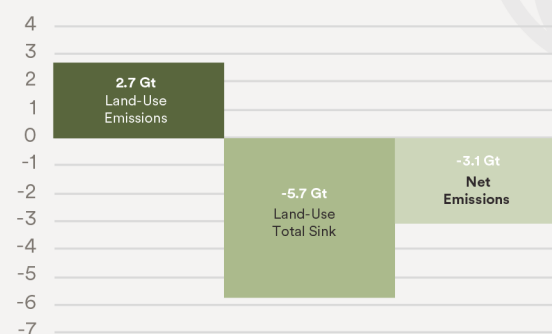


FIGURE 23: LAND USE SECTOR

Global land-use emissions (GtCO₂e/yr)



2050 land-use emissions, sink, and net emissions (GtCO₂e/yr)



2050 total mitigation by region (GtCO₂e)

	Global	Asia (RO) and		Brazil	C Asia, M East, Russia		China	Europe	India	Latin America (RO)		SE Asia	U.S.A. & Canada
Crops	-2.8	-0.9	-0.1	-0.3	-0.3	-0.3	-0.2	-0.3	-0.2	-0.2	-0.2	-0.1	-0.3
Biomass	-1.1	-0.3	0.0	0.0	-0.3	0.0	-0.2	0.0	0.0	0.0	0.0	-0.1	-0.1
Other Natural	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Urban	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Unmanaged Land	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Shrubland	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Grassland	0.7	0.4	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0
Pasture	0.8	0.4	0.0	0.2	0.2	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.1
Other Arable	1.3	0.6	0.1	0.1	0.2	0.0	0.1	0.1	0.1	0.1	0.0	0.0	0.0
Forest	0.5	0.7	0.1	0.7	0.9	0.3	0.5	0.2	0.4	0.4	0.4	0.8	0.8
TOTAL	4.0	0.9	0.1	0.7	0.6	0.2	0.2	0.1	0.3	0.3	0.3	0.5	0.5

In 2050, compared with a Reference scenario, the Central scenario reduces land-use related emissions by around 4 GtCO₂e. This is around 6% of total mitigation distributed across multiple land use types. This number hides the carbon flux or gross accounting of emissions between land use types. As seen in graphic on the right, there are produced emissions and removals. Typically, the net number is reported to avoid confusion on the gross accounting, but the table shows mitigation by each individual land-use type. Because these are reported as mitigation (the difference between the Reference and Central scenarios), the sign is flipped, with negative numbers representing land use types that produce more emissions than in the Reference scenario, while a positive number indicates mitigation similarly to what is reported in other sectors. Totals might have a slight mismatch due to rounding.

Forest and land use Ensemble results

The Ensemble scenarios envision a total halt to deforestation in the coming years and therefore reach net-zero emissions by 2025. In the longer term, the Central scenario reaches a net reduction of $\sim 3 \text{ GtCO}_2\text{e}$ by 2050 and the L-TEL scenario achieves the most significant net reduction by 2050 at $-3.5 \text{ GtCO}_2\text{e}$. Meanwhile, the H-BIO scenario has a smaller sink, at only $-1.8 \text{ GtCO}_2\text{e}$ by 2050.

Globally, the Central scenario shows a reallocation between land types of around 3.4 million km^2 between 2020 and 2050, which is less than 3% of total land. This represents between 80,000 and 140,000 km^2 per year, or around 0.1% annually. Trends emerge in the Ensemble when it is compared with a Reference case (see Figure 24), which largely mimics historical trends (e.g., increases of crop and grazing lands as natural lands are reallocated). The Central scenario and Ensemble reverse such trends and see a reduction of crop and grazed lands, reallocating these toward forests, pastures (meadows), grasslands, and bioenergy production.

Bioenergy is highly constrained in the Central (considered a L-BIO scenario) and across most scenarios, resulting in modest land allocation for that use (around 850,000 km^2 , or just over half of the 1.6 million km^2 seen in a Reference case). However, the M-BIO and H-BIO scenarios showcase how this might be different. In the H-BIO scenario, we see the greatest amount of land reallocation at around 6.7 million km^2 , or about 5% of land. In these scenarios, land transfers go to bioenergy production and illustrate key trade-offs when balancing land options with energy. In 2050, the Central scenario has 69 exajoules (EJ) of bioenergy while the M-BIO and H-BIO scenarios have 131 EJ and 219 EJ, respectively.

Forests and land use: insights and pathway implications

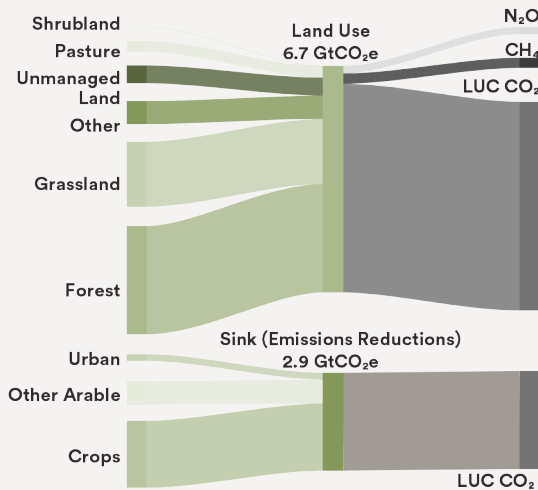
Lands and forests provide sustenance, protection, and resources. They are essential to climate mitigation and climate restoration as scalable sources for the natural capture of carbon emissions. However, as envisioned in ClimateWorks scenarios, such climate services require tailored approaches across land types, geographies, and peoples. These include protecting existing carbon stocks while also reallocating less productive, marginal lands toward climate-beneficial uses, which in turn requires aligning complex policy environments that seek to balance demands for food, fuel, resources, and climate services.

In some geographies, this implies securing and implementing policies already in place where enforcement may be weak. In such places, stronger land rights must be secured for communities engaged in sustainable stewardship practices. Elsewhere, knowledge gaps exist regarding the potential impacts and financial risks associated with the loss and degradation of ecosystems. By aligning incentives and strengthening the implementation of existing policies, the forest and land use sector can shift from being a major emitter to a net carbon sink while also benefiting local communities.

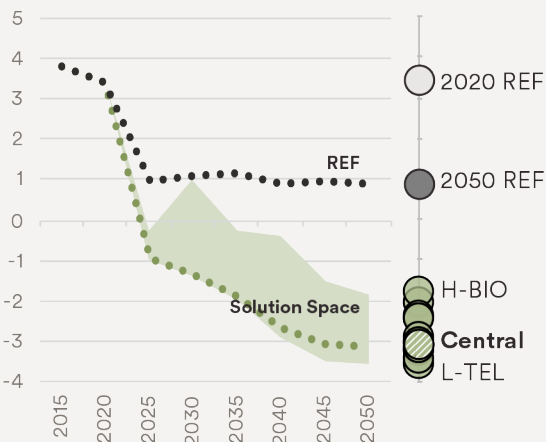


Land Use

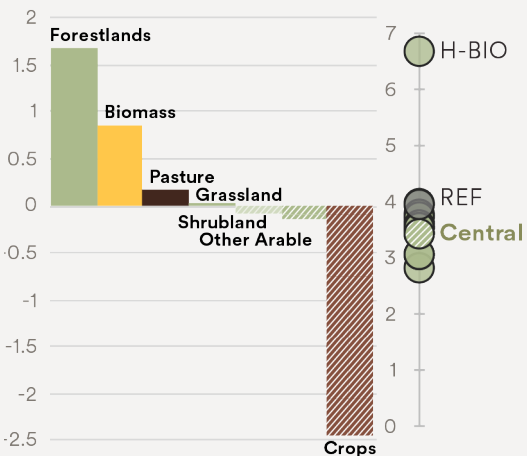
a. 2015 land-use emissions flows (3.8 GtCO₂e of associated emissions)



b. 2015-2050 land-use emissions (GtCO₂e/yr)



c. Gross land shift 2020-2050 (mil km₂)



d. Shift (mil km₂)

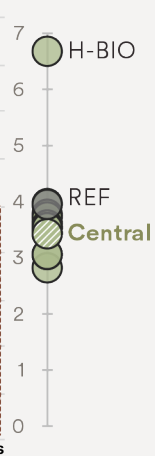
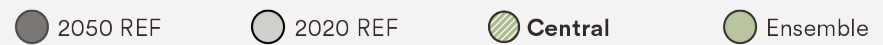
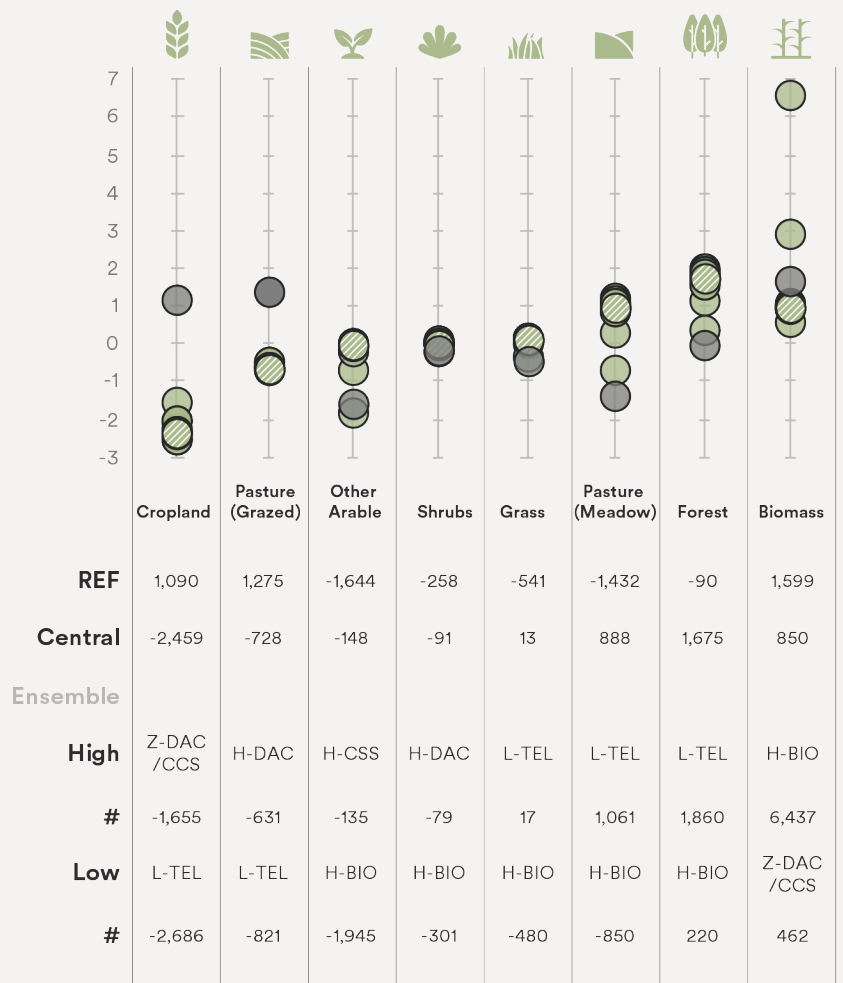


FIGURE 24: LAND-USE SECTOR DASHBOARD

- This figure shows the flow from end use to greenhouse gas. The Sankey is divided into two components: emissions (top) and emissions reductions or sink (bottom). Land Use shows data from 2015 since numbers for this sector are more reliable than current ones. For a more detailed view, please refer to the Technical Summary (TS Table 6)."
- The gray dotted line displays the net emissions for the Reference case and the light green line displays the Central scenario. The green shaded area represents the range of values for the full Ensemble. The scatter plot on the right takes the 2050 values of this graph displaying the Ensemble and Central scenarios and Reference case for 2020 and 2050.
- The graph shows the gross shifts across land types between 2020 and 2050 for the Central scenario in km².
- This shows the total shift amount in million km² between 2020 and 2050 by use across the Ensemble as well as a comparison with the Reference case and the 2020 values.
- The table highlights the highest and lowest shift values for land-use types across scenarios with its high and low values for the Ensemble showing variation based on scenario narrative.



e. 2020-2050 Ensemble scenarios land shifts (mil km²)



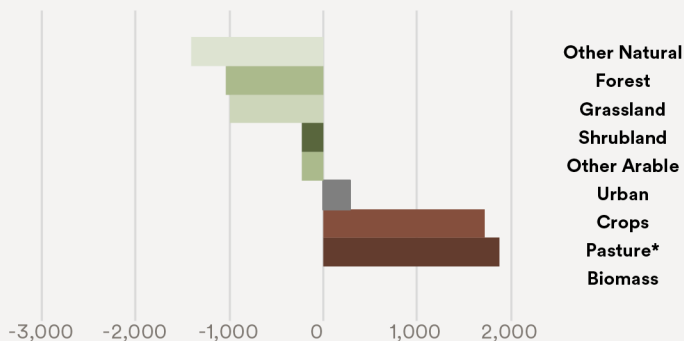
Linkages to land use

The Central scenario envisions a large transition in land-use sectors in which deforestation trends halt in the near term and reverse over the next three decades, while also sparing land for a constrained bioenergy sector. Historically there have been large global shifts associated with the reallocation of natural lands toward cropland and pastureland (see Figure 25, panel a). This trend reverses in the Central scenario, and by 2050 a combination of enhanced agricultural practices and dietary shifts free up land for reforestation and afforestation and the production of valuable bioenergy and sustainable wood products. There is also a reallocation of marginal lands (those with little or no agricultural or industrial value) from multiple land types, including grasslands, shrubland, and other arable lands.

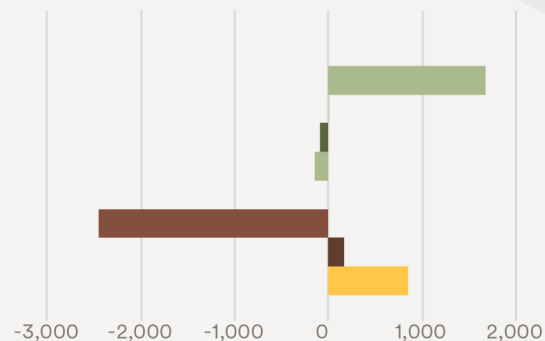
In total, roughly 370 million hectares (less than 3% of global land area) are reallocated between 2015 and 2050. Around 72% of this comes from marginal cropland and an additional 21% from pastureland, while more productive land is reserved for continued food production. Figure 25 (b and c) showcases the net and detailed transitions for each land type for the Central scenario. As with the energy sector, it is necessary to take an integrated systems approach to mitigation to reveal the full spectrum of these interactions. In the case of land sectors, this shows how food and agricultural production and potential shifts in practices are integral to a climate services approach that emphasizes the potential for natural carbon dioxide removal in other land types.

FIGURE 25: GLOBAL HISTORICAL LAND TRANSITIONS AND GCAM-CWF SCENARIO TRANSITIONS 2015-2050 BY CATEGORY

a. Historical land-use transitions 1975-2015 (million km)



b. Central scenario transitions 2015-2050 (million km)



c. Scenario land reallocation by land type 2015-2050 (million km)



Figures a and b show historical and future land reallocation from land use. We can observe the largest future increase is in forest and biomass, and this is mainly achieved by a large reduction of crops and pasture.

Figure c shows an increase in land reallocation to biomass and forest. Crops reallocate land to other uses, mainly forests, pasture, and biomass. (*Note that some forestland is reallocated to bioenergy, but this is offset by large amounts of reallocation from other land types).

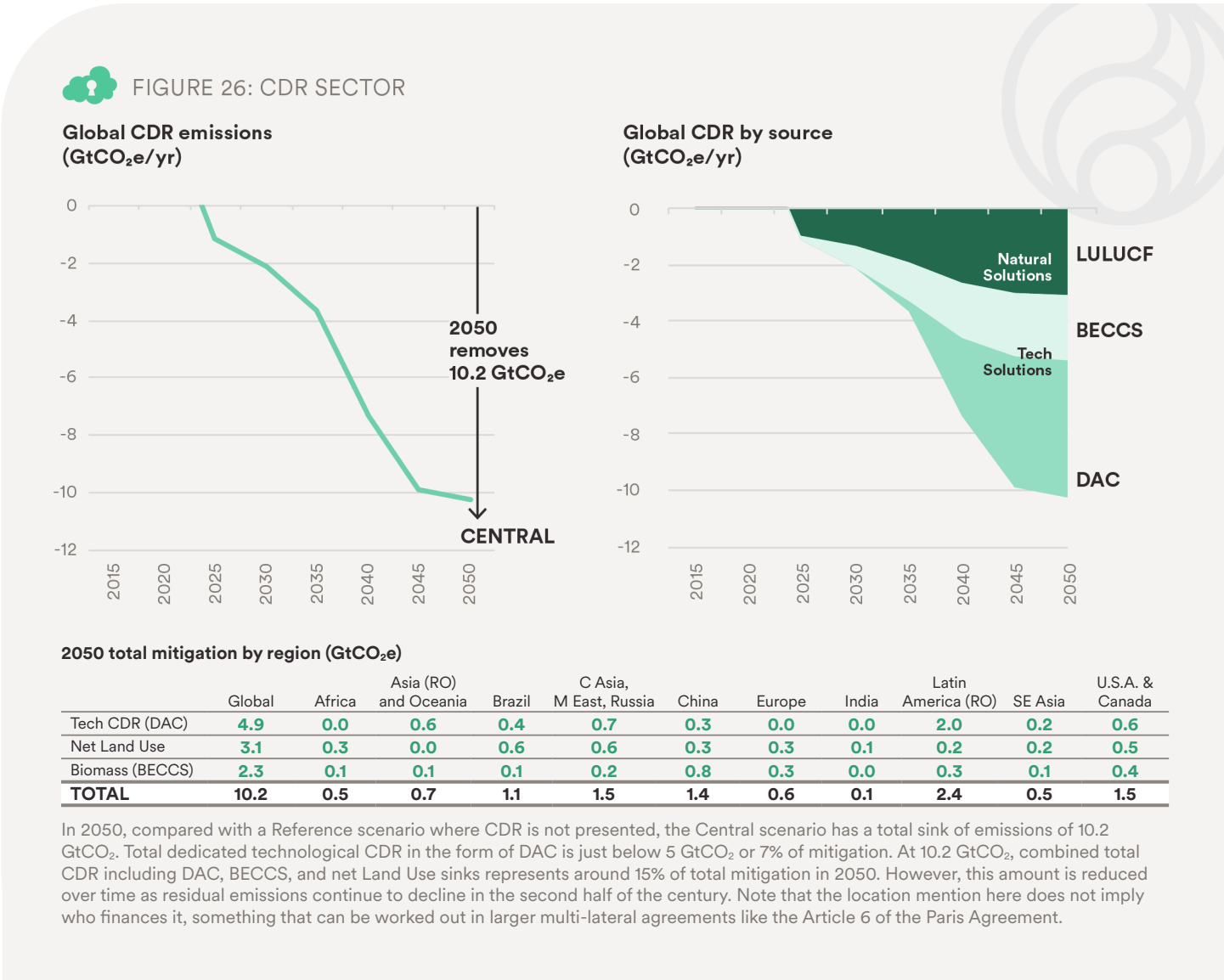
*Pasture shows an increase in land allocation due to the grouping of pasture type. This means that pasture allocated to meat production is reduced and pastureland increases. The increase observed in this graph is mainly pastureland meadows that have associated sinks.

**Such a high volume of reallocated cropland may seem counterintuitive. Note, however, that the cropland reductions are largely from marginal or less unproductive lands.

Carbon dioxide removal

We organize CDR into three categories: *natural solutions* that use the planet’s inherent ability to sequester carbon through land-use practices; *technological solutions* that use new or existing technologies to sequester carbon; and *mixed solutions* that utilize both natural and technological approaches, as is the case with BECCS. The previous section on forests and land use provides more details on natural solutions. The Central scenario scales natural carbon sinks to around 1.3 GtCO₂ and 3 GtCO₂ by 2030 and 2050, respectively. These sinks are dominated by reforestation and afforestation but also include regenerative agricultural methods; grasslands and other natural lands play a role as well. Technological CDR includes the use of DAC and BECCS, with the latter curtailed due to constraints on bioenergy. There are also constraints on DAC in the Central Scenario. BECCS reaches a total sink of 0.8 Gt by 2030 and 2.3 Gt by 2050, while DAC reaches a total of 0.04 Gt by 2030 before scaling quickly to nearly 5 Gt by 2050. By 2050, total CDR is just above 10 Gt (see Figure 27 for alternate scenarios and the Technical Summary TS 7, 9 and 10 for comparison with other studies).

As with earlier modeling, we treat these technological CDR options as proxies for a wider potential portfolio of options. Other CDR options include new, enhanced versions of DAC, ocean alkalinity enhancement, direct ocean capture, enhanced weathering, and other options like biochar, engineered wood, and the conversion of CO₂ to durable carbon for use in consumer products and fuels. These need to be further explored by the scientific and research community before they are included in the model.



CDR Ensemble results

There is significant variation across pathways for CDR, with a total range of around 9.4 GtCO₂ by 2050 (sinks range between 2.4 GtCO₂ and 11.8 GtCO₂). The lowest level of CDR occurs in the Zero-DAC/CCS scenario, which limits all forms of technological CDR. Meanwhile, the M-DAC and H-DAC scenarios achieve the most significant emissions removals by 2050, followed by M-BIO and H-BIO scenarios. In both of these sets of scenarios, the constraints are progressively lifted so that the high scenarios show a very different picture.

There are trade-offs when comparing across the CDR categories (nature-based, technological, and mixed [BECCS]). Ultimately, total CDR has larger trade-off implications when used as a balance to residual emissions, although feasibility is debatable, as are the costs, risks, and utility of each type. Additionally, the options for CDR are expanding, and we are researching ways to include more types of CDR. (See our [recent report](#) in Nature Climate Change on diverse carbon dioxide removal approaches.) In the meantime, we use the three categories as approximations, aware that newer entrants may have comparative advantages that will ultimately change the totals. For now, Ensemble results indicate sinks in 2050 for natural CDR ranging from 1.8 GtCO₂ to 3.5 GtCO₂, technological CDR from 0 GtCO₂ to 7.3 GtCO₂, and mixed CDR from 0 GtCO₂ to 7.1 GtCO₂. Average removal outcomes for these are 2.9 GtCO₂, 4.3 GtCO₂, and 2.5 GtCO₂ for natural, technological, and mixed CDR, respectively. (See Figure 27, for detailed results.)

CDR: insights and pathway implications

Requirements and the potential scale of CDR are actively debated, with a wide range of opinions across research, policy, and advocacy communities. On the advocacy side, some fully endorse the use of CDR while others view it as a moral hazard that should be avoided altogether. Opponents argue that, given scarce resources, a focus on CDR takes away from a necessary emphasis on reducing emissions. They also raise concerns that technological forms of CDR and the accompanying infrastructure may have adverse effects on ecosystems and communities. Meanwhile, supporters of CDR see it as a necessary component of any successful effort to limit warming to 1.5° C and reduce overshoot — a view that has been validated in scientific literature, including the IPCC's most recent assessment report.¹⁹ Advocates see downside risks as addressable. Ultimately, more work needs to be done to fully assess the environmental and social concerns associated with scaling technological CDR.

While the Ensemble of scenarios in this report consider CDR as a necessary approach, we emphasize the need to engage with relevant groups and communities to mitigate any deleterious effects. The Ensemble scenarios provide a range of CDR options, including one that bars technological CDR altogether (Zero-DAC/CCS). However, such a highly constrained scenario results in higher temperature outcomes, implying a significant trade-off when CDR is not scaled sufficiently as an option to balance annual emissions and remove historical emissions. As this debate continues, there is new research emerging on a wider set of CDR options that allow the deployment of a portfolio of measures, thereby reducing reliance on any single option. We will continue engaging on this important topic by assessing the latest research and bringing learnings into future analyses.



Land Use

Natural solution that uses the planet's ability to sequester carbon through land-use practices. This is covered in Land Use section in more detail.



BECCS

Technological solution that uses biomass to generate bioenergy.



Tech CDR

Technological solution that captures CO₂ directly from the atmosphere.

FIGURE 27: CDR SECTOR DASHBOARD

- The graph represents the range of values for the full Ensemble. The dotted line is the Central scenario. The scatter plot on the right takes the 2050 values of this graph displaying the Ensemble and Central scenarios. Most of the scenarios within the Ensemble aim to reduce between 10 and 12 GtCO₂e. Only two scenarios, Z-DAC and Z-DAC/CCS, are more conservative and reduce only 3 and 2.4 GtCO₂e, respectively.
- The graph shows the total sink for natural solutions (LULUCF), combined natural and technological solutions (BECCS), and dedicated technological (DAC).
- This shows 2050 sinks across the ensemble by category. The table highlights the highest and lowest scenario with its value across the Ensemble showing variation based on scenario narrative. The larger the reduction for each technology, the higher negative numbers, since it shows CO₂e reductions.

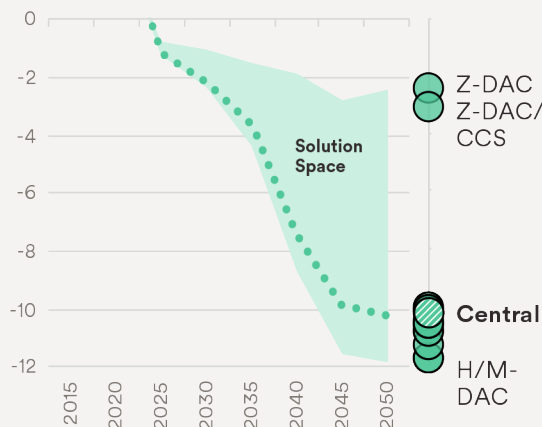


Central

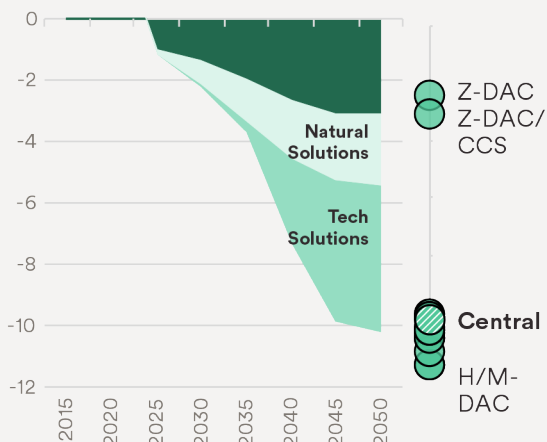


Other Ensemble

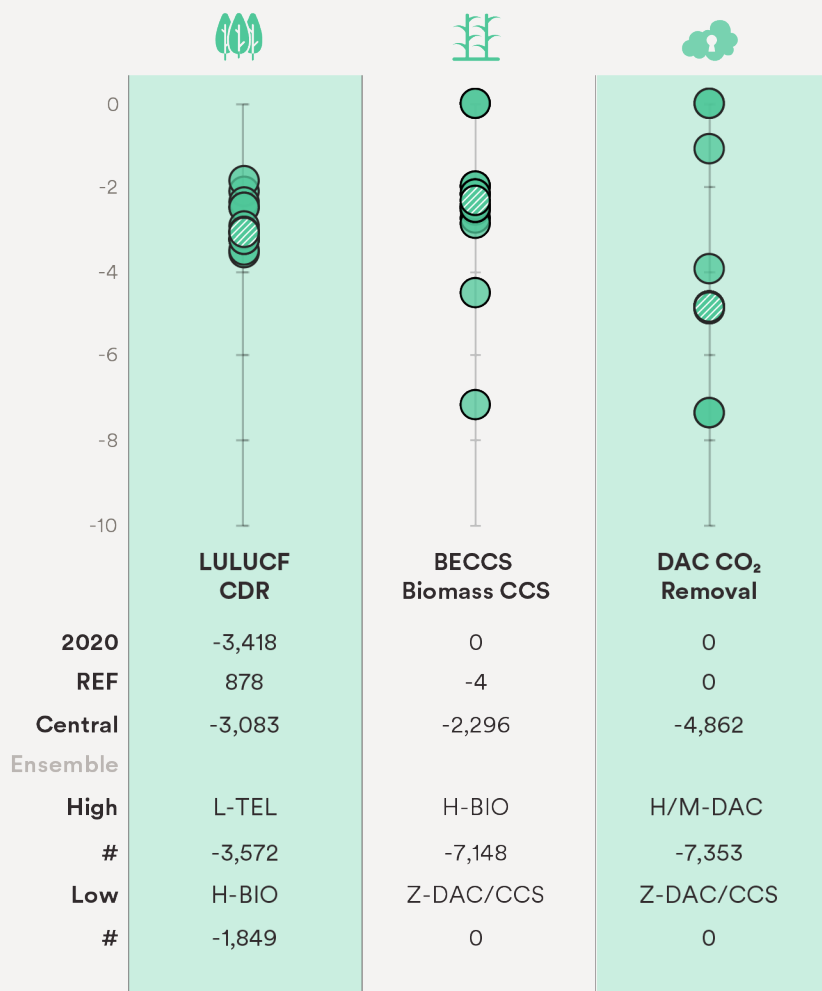
a. 2015-2050 CDR emissions reductions (GtCO₂e/yr)



b. CDR solution space 2015-2050 (GtCO₂e/yr)



c. 2050 other Ensemble scenarios (GtCO₂e/yr)



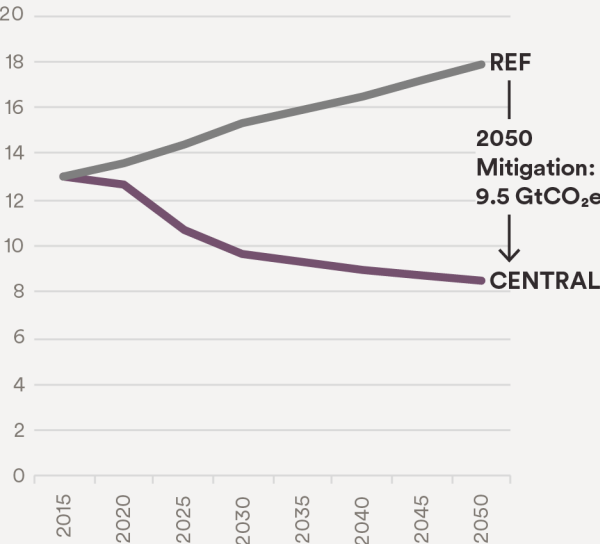
Super pollutants

We refer to the non-CO₂ share of greenhouse gases as “super pollutants “; these include methane (CH₄), nitrous oxide (N₂O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) like hexafluoroethane (C₂F₆) and tetrafluoromethane (CF₄), sulfur hexafluoride (SF₆), nitrogen trifluoride (NF₃), and black and brown carbon. Reductions to super pollutants come from a variety of sectors, as outlined in Figure 28, and in this section, we group these various pollutants together to assess their overall contributions. The Central scenario collectively reduces super pollutants by more than 29% by 2030 and 38% by 2050 (combining F-gases, N₂O, and CH₄), compared with 2020 levels. These are reductions of nearly 5.7 GtCO₂e by 2030 and 9.5 GtCO₂e by 2050 compared with a Reference case. While not included in the figures below, emissions related to black carbon are also reduced. There is a large range of uncertainty in applying 100-year global warming potential to black carbon,²⁰ as it depends on the source location. However, black carbon is important for inclusion when considering benefits beyond climate, like public health. In addition to their potency as greenhouse gases, super pollutants are associated with poor health and mortality through respiratory diseases, as well as local environmental degradation. Aggressively reducing emissions of these pollutants supports a healthy climate while also providing significant public health, social, and economic benefits.

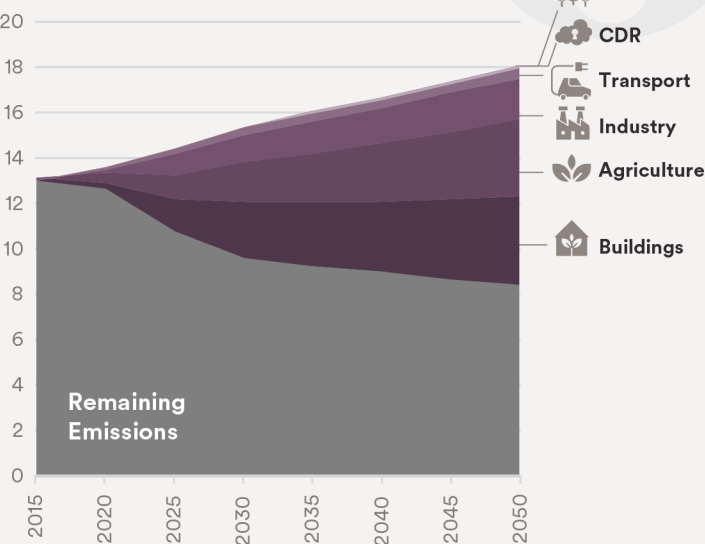


FIGURE 28: SUPER POLLUTANTS SECTOR

Global super pollutants emissions (GtCO₂e/yr)



Mitigation by source (GtCO₂e/yr)



2050 total mitigation by region (GtCO₂e)

	Global	Africa	Asia (RO) and Oceania	Brazil	C Asia, M East, Russia	China	Europe	India	Latin America (RO)	SE Asia	U.S.A. & Canada
Electricity	0.3	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Fuel Supply	2.1	0.1	0.1	0.0	0.6	0.3	0.2	0.0	0.2	0.2	0.4
Agriculture	3.4	1.1	0.2	0.2	0.3	0.4	0.2	0.3	0.2	0.2	0.2
Buildings	2.8	0.3	0.3	0.1	0.5	0.5	0.2	0.2	0.2	0.4	0.1
Industry	0.6	0.2	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0
Land Use	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Transport	0.2	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
TOTAL	9.5	2.0	0.7	0.3	1.5	1.4	0.7	0.6	0.6	0.9	0.8

In 2050, compared with a Reference scenario, the Central scenario reduces land-use related emissions by around 9.5 Gt CO₂e. This is around 13.5% of total mitigation distributed across multiple sectors and greenhouse gases.

Super pollutants ensemble results

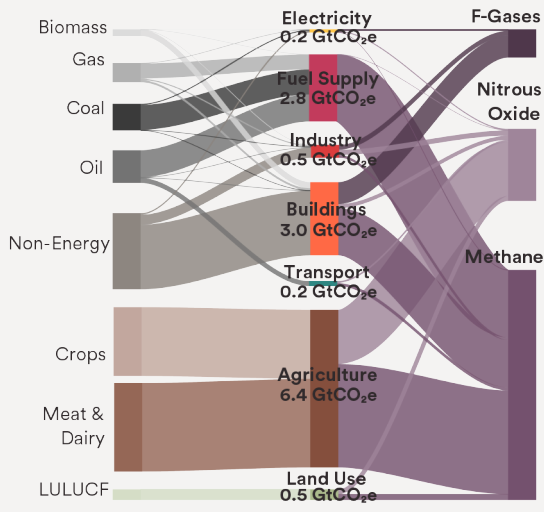
Super pollutants vary only slightly across scenarios within the Ensemble, with a range of 0.9 GtCO₂e. The scenario with the highest emissions by 2050 is the H-BIO scenario, with 9.2 GtCO₂e; the lowest is the L-TEL scenario, with 8.3 GtCO₂e. The Central scenario results in approximately 8.5 Gt by 2050, and most scenarios within the Ensemble align with this outcome. This reflects the fact that the current scenario narratives focus largely on technologies that more closely affect carbon dioxide outcomes. We hope to address this dynamic in future research by building out more scenarios that directly impact super pollutants, thus providing a larger range of outcomes.

However, this does not mean that the narratives exclude direct modeling for super pollutants. Instead, it shows that such modeling is more uniform across the Ensemble results. For example, each scenario includes the Kigali Amendment to the Montreal Protocol, which aims to curtail F-gases and is the reason buildings-related emissions contain a large share of the reductions (see Figure 29) as these relate to space-cooling devices. We see similar responses in the other two largest sectors impacted: fuel supply and agriculture. In fuel supply, a shift in demand away from fossil fuels reduces the overall methane emissions associated with the extraction, processing, and distribution of these fuels, but so does a direct focus on avoiding fugitive emissions through a retooling of such industries. In agriculture, there is a similar set of demand and supply interventions through dietary shifts, and thus a reduction in methane associated with meat consumption, but also productivity measures on farms and especially in the production of rice, which similarly reduces methane.

Super Pollutants

FIGURE 29: SUPER POLLUTANTS DASHBOARD

a. 2020 super pollutants emissions (13.6 GtCO₂e)

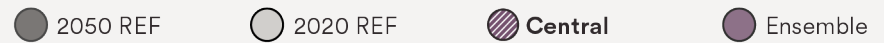


a. Figure a shows the flow from direct source to sectors, finally splitting into the types of super pollutant gas. With 6.4 GtCO₂e, Agriculture had the largest non-CO₂ emissions, composed mainly of methane and nitrous oxide. Buildings had the second largest with 3.0 GtCO₂e, followed by Fuel Supply with 2.8 GtCO₂e. For an in-depth view of this Sankey flow as well as detailed amounts of emissions, please refer to the Technical summary (TS Table 6).

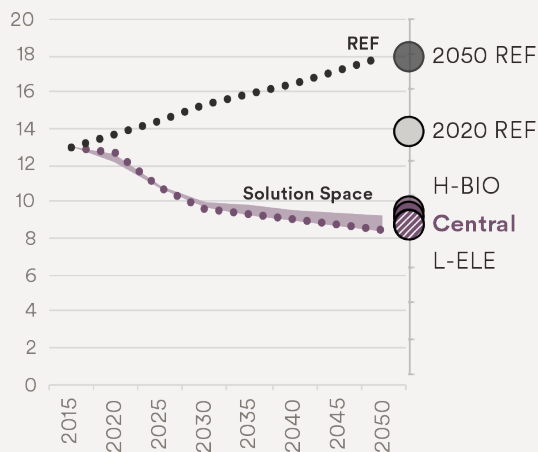
b. The gray dotted line displays the Reference case and the purple line displays the Central scenario. The small purple-shaded area represents the range of values for the full GCAM-CWF Ensemble. The scatter plot on the right takes the 2050 values of this graph displaying the Ensemble and Central scenarios and Reference case for 2020 and 2050.

c. The largest solution space in terms of GHG reductions is from Methane, followed by F-gases and lastly Nitrous Oxide. The Central scenario achieves a 67% of reductions or 6.3 GtCO₂e from methane in 2050. Collectively, super pollutants can reduce up to 9.5 GtCO₂e by 2050.

d. This shows 2050 generation shares by technology across the Ensemble as well as a comparison with the Reference case and the 2020 values. The table highlights the highest and lowest scenario with its value across the ensemble showing variation based on scenario narrative.



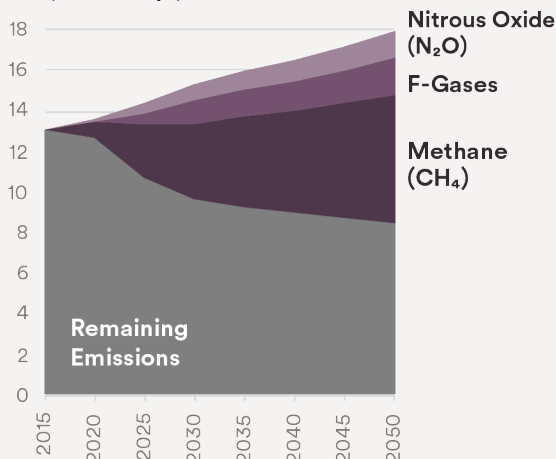
b. 2015-2050 super pollutant emissions reductions (GtCO₂e/yr)



d. 2050 other Ensemble scenarios (GtCO₂e/yr)



c. Mitigation by GHG (GtCO₂e/yr)



Ensemble assessment and discussion

Beyond implications for individual sectors, it is beneficial to consider the broader learnings from and implications of the Ensemble scenarios exercise more generally. Interpreting the results and forming insights is a complicated process. By design, these scenarios are meant to test the sensitivity of parameters, thereby informing a discourse on their use, with such discourse focusing on the costs, feasibility, reliability, substitutability, and advisability of interventions. Subjectivity is all but unavoidable due to the shifting and complex nature of how we derive and place value on different interventions. This subjectivity has direct consequences for what elements within a pathway are emphasized and can become a box-checking exercise for key questions including: Is bioenergy constrained, and by how much and when? How are BECCS and other CDR options used, and at what pace? Is there an overshoot of 1.5° C? Is nuclear energy curtailed or incentivized? What are the mid-century shares of renewable energy generation, and are wind and solar prices up to date?

The specific set of questions (and the implied set of expectations) further constrain the degree of freedom with which one can meet all expectations while remaining consistent with a 1.5° C outcome. And yet, constraints and incentives represent important societal considerations and values and should be weighed with proper attention to alternative outcomes. These results are a snapshot and formulated among shifting policy and research environments. We treat this exercise as an ongoing process and continue to stay informed through discussions with our partners.

Table 2 attempts to highlight some of the insights and considerations resulting from the Ensemble results, but these should *not* be treated as exhaustive. More details and discussion of the assumptions behind each of the scenarios can be found in the Technical Summary that follows. For each scenario set in the table (bioenergy, CCS, DAC, nuclear, RE, and transport electrification), we describe some of the interactions that occur as a result of constraints or incentives deployed. Essentially, whenever something is constrained or incentivized, there are trade-off considerations.

The following insights were taken into account to determine the choices made for the key parameters in the Ensemble chosen.

TABLE 2. ENSEMBLE INSIGHTS AND CONSIDERATIONS THAT DETERMINE THE CHOSEN SCENARIO

Scenario set	Type (Central designation)	Results discussion	Sector considerations
Bioenergy	Low, medium, high	Bioenergy can be a gas, liquid, or solid fuel, making it an attractive substitute for more carbon-intensive fossil fuels. It can serve as the dominant mitigation option but at a cost, as land use implications can be wide ranging.	All land and energy sectors are affected
		Limiting bioenergy curtails the availability of less carbon-intensive fuels and some CDR options. When these are constrained, other interventions increase, such as the use of electrification of end uses and uses of fossil CCS and nuclear energy. The use of unabated fossil fuels decreases precipitously. Competition for land decreases, lowering crop prices, but re/afforestation increases.	
		When bioenergy is increased, the use of electrification, fossil CCS, and nuclear declines. Fossil fuels exit more slowly. Major disruptions occur in land use sectors, with a shift toward dedicated bioenergy production in place of croplands and re/afforestation. Crop prices rise.	
Carbon capture and sequestration (CCS)	Zero, low, medium, high	CCS is double-edged. Its widespread use allows a slower shift away from fossil fuels. Constrained use of CCS places a large burden on natural forms of CDR to compensate for residual emissions from unabated fossil use in sectors that have limited fuel-switching options. Temperature targets are much harder to achieve.	CCS variation affects generation and industry
		When CCS is constrained, electrification increases and fossil fuels decrease quickly. The use of zero-emissions fuels and generating technologies increases (including nuclear). The need for re/afforestation increases to make up for the loss of CDR options. Crop prices rise due to this pressure on natural CDR.	
		When CCS is increased and incentivized, a predictable lifeline is provided to fossil fuels for use in electricity generation, industrial applications, and refining.	

Direct air capture (DAC)	Zero, low, medium, high	DAC is used as a proxy metric in the Ensemble representing forms of CDR other than re/afforestation and BECCS. CDR remains an essential part of any high-ambition, high-probability, low-temperature pathway as it balances out residual emissions and compensates for historical emissions, allowing temperatures to decrease. When constrained, residual emissions across all sectors must decline. Other CDR options like re/afforestation and the use of BECCS place greater stress on land systems. When completely constrained to zero, the pathway has a lower probability of remaining at or below 1.5° C by 2100. When increased, residual emissions increase, and the price of carbon falls, influenced by the cost of DAC. Scalability concerns grow, as does energy use. Pressure on land is reduced.	All energy and land sectors
DAC and CCS	Zero	This scenario represents a failure of both CCS and DAC to materialize. This triggers a need for the lowest possible residual emissions. Efficiency and electrification scale most rapidly. The grid becomes near-zero rather than net-negative as BECCS is not an option. Pressure on land increases as re/afforestation becomes the sole source of CDR, and bioenergy demand spikes if not constrained. Temperature overshoots are highest, and the probability of returning to 1.5° C is at its lowest.	All energy and land sectors
Nuclear generation	Zero, low, medium, high	While RE remains the dominant choice of generation, nuclear competes with other forms of net-zero emissions generation like energy storage options and CCS. Given this, increasing nuclear deployment reduces those technologies, and decreasing nuclear has the opposite effect. Beyond generation, there is little effect due to this substitutability. When nuclear energy is constrained, energy storage and use of fossil CCS increase to make up for losses in flexible baseload generation. As a result, costs are assumed to rise. When nuclear energy increases, the most profound effect is on energy storage and use of fossil CCS, both of which are reduced significantly. Economies of scale and reduced need for storage are assumed to reduce costs. RE remains dominant, and so these adjustments affect the remaining smaller shares of the grid.	Only generation
Renewable energy	Low, medium, high	Renewable deployment in generation is a foundational mitigation strategy with fewer concerns than alternative zero-carbon generating technologies like CCS and nuclear. Still, ever-larger shares of RE require grid stability mechanisms like energy storage. When RE is constrained and the potential longer-term share decreases, other zero-carbon generation technologies rise, like CCS and nuclear. The need for energy storage decreases. High amounts of efficiency and electrification are rapidly deployed among buildings and industry end uses, thereby reducing residual emissions that might otherwise require CDR. When RE increases, the need for other zero-carbon generation using CCS or nuclear is reduced. However, as RE rises, so does the need for energy storage.	Generation and end use when low
Transport electrification	Low, medium, high	Increased electrification, when paired with a zero or net-negative grid, allows end uses to significantly reduce residual emissions. Road transport electrification is particularly attractive due to efficiency and emissions savings. When the electrification of road transport is increased, reaching 100% of new vehicle sales by 2050, residual emissions all but disappear from these modes, requiring less CDR. Demand for electricity increases, but the total cost of mitigation declines. When the electrification of road transport decreases, residual emissions in this sector increase, triggering a need for either increased CDR or reductions in other end uses. Electrification occurs at higher rates in buildings and industry to compensate. Liquid fuels from oil and bioenergy remain high, and the total cost of mitigation increases.	Demand for electricity changes, as does need for residual emissions reduction in other end-use sectors

Putting it together: links, dependencies, timing, and use

In the previous sections, we highlighted some cross-sectoral linkages, such as the connection between end-use sectors and energy supply. Importantly, there are additional considerations related to path dependencies or the timing of measure prioritization due to the interdependencies of solutions. For example, while electrification is the endgame, there are numerous measures (like efficiency) worth considering during what is often called the “messy middle,” when electricity generation is retooled toward net-zero emissions technologies. For emissions reductions to accrue most rapidly, the emissions intensity of electricity (that is, CO₂ emissions per unit of energy generated) must decline precipitously while generating capacity increases. To this end, the model deploys rapid scaling of RE but also a retrofitting of thermal plants to include CCS technologies. However, this should not be viewed as a foregone conclusion or a prescription for achieving a 1.5° C pathway, as other interventions may be deployed. The aim of the Ensemble is ultimately to show how perceptions of pathway dependencies may change with our understanding of the potential for interventions – land or energy related – to contribute.

For example, a broad land-use strategy designed to reduce deforestation, protect existing forest sinks, promote afforestation, improve agricultural productivity, and promote sustainable food choices must be weighed against the trade-offs on how land might otherwise be used to grow crops for fuel or produce material substitutes for our built environments. Such choices impact a myriad of solutions elsewhere, including how much CDR (both natural and technological) may be required to balance out the residual or remaining emissions that are slower to exit from energy and land systems. The Central scenario and accompanying Ensemble take many of these trade-offs into account, and robust and inclusive strategy development that takes community input into account might help reveal these interconnections and trade-offs.

Creating strategies that deliver on these opportunities requires further work to transition from this expansive view toward increasing detail on the mechanics of mitigation, intelligence from the field seeking to enact these transitions, and the philanthropic levers that enable them. Together these provide a simple conceptual framework to help any climate actor develop effective strategies, including philanthropy (see “Using the ClimateWorks Ensemble” in the Technical Summary for more discussion of how we use this framework). ClimateWorks is committed to producing research that will help bring these together. In 2021 we used this framework to publish a brief on the transportation sector (see: <https://www.climateworks.org/report/program-strategy-brief-transportation/>). We intend to further evaluate additional sectors, explore key factors worth considering from the field, and provide examples of the philanthropic levers that enable policy and behavioral changes and can unlock other capital and actors to enable such changes. Such evaluation will build upon the contexts described in each of the sectors above and utilize the results throughout this report.

Ultimately, understanding the complexities of these interwoven considerations — the scale and mechanics of the mitigation, the field capacity to enact these transitions, and the levers that enable them — can help funders prioritize investing in high-impact GHG reduction opportunities.

Technical Summary

Technical summary primer

The main body of the report provides a high-level overview of data and results for climate change mitigation scenarios. This technical summary presents additional details and a discussion of the modeling framework, assumptions, and results as well as comparisons with other modeling projects. This summary was created as a standalone document and replicates some of the information outlined in the main body of the report. Our aim is to provide additional information for those interested in a more detailed exploration of mitigation scenarios. However, we also understand that advanced modeling projects are inherently complex and that there are tensions among levels of detail, transparency, and maintenance of a coherent and consistent narrative. Those interested in a more detailed analysis or explanation of the modeling are welcome to contact us at info@climateworks.org and to provide input or inquiries.

Components of the model

Our scenarios build on the Global Change Analysis Model (GCAM), an integrated assessment model (IAM) developed by the Joint Global Change Research Institute (JGCRI), a partnership between the University of Maryland and the Pacific Northwest National Laboratory (PNNL). IAMs vary in terms of the complexity of their modeling environments, but the overarching goal of these models is to evaluate the interaction among systems — how societal choices and economic development affect and interact with natural Earth systems. They provide a framework for evaluating the potential knock-on effects and trade-offs of certain climate interventions and for considering a risk management approach as various mitigation options are deployed at a global and regional level. To provide such a framework, GCAM blends economic and scientific understanding into a numerical framework. Scenario assumptions such as population, labor productivity, technological characteristics, and policies are fed into the model, which generates an “optimal” pathway through recursive runs, resulting in the outputs of the modeled scenario.²¹ These outputs range from data on emissions outcomes, prices, energy demand, agricultural productivity, emissions concentration, and other crucial factors that inform the discourse on how policy choices might influence future climate outcomes.

GCAM has extensive sectoral, technological, and geographic representation. Importantly for ClimateWorks, GCAM is an open-source model, which allows us to connect data and insights across our various programmatic work and for all our key geographies while also making data available to relevant parties. Key components of GCAM include coverage of 24 species of greenhouse gases, including CO₂, CH₄, N₂O, halocarbons, carbonaceous aerosols, reactive gases, and sulfur dioxide. GCAM is a Representative Concentration Pathway (RCP) class model that can simulate scenarios, policies, and emissions concentration targets. GCAM is widely cited and used in academic literature, including the Intergovernmental Panel on Climate Change’s (IPCC) Assessment Reports (AR) for which JGCRI scientists have engaged in working groups. Land, energy, and water are tightly coupled in the model:

- **Land Use:** GCAM includes 384 land regions with 18 types of agroecological zones. The land resource mapping units are defined in terms of climate, landform, and soil to allow the modeling of land use and land use change activity and emissions.
- **Energy:** GCAM covers 32 energy and economic regions, including all major economies (see Table TS6 for geographic detail). Energy sectors have technology-rich representations with myriad mitigation options.
- **Water:** GCAM includes a global hydrological model with 235 hydrological basins. This model includes a technologically detailed representation of water demand sectors, along with withdrawal and consumption.²²

As mentioned, the GCAM-CWF Central scenario (or simply Central) builds on the Shared Socioeconomic Pathway 1 (SSP1, the Sustainable Development scenario) as an extension. Many of the narrative elements in SSP1 are mirrored in the Central scenarios, including those capturing sustainability, inclusive development, human well-being, development goals, and macroeconomic indicators (GDP and population pathways). However, the GCAM-CWF scenario goes further

by accelerating or decelerating some of the human and technological components to meet a stringent low-emissions pathway while respecting planetary boundaries and pursuing Sustainable Development Goals as highlighted by ClimateWorks and our many philanthropic partners.

Scenarios discussion

Before providing more detail on the scenarios, we explain the reasons we have so many scenarios, how we might make good use of them, and why we are not using scenarios from other sources.

Defining our scenarios

In our 2020 report, we referred to the *Nature Climate Change* article, “The appropriate use of reference scenarios in mitigation analysis” and used its descriptions of scenarios as shown in the table below.

TABLE TS1: THE FOUR DIFFERENT REFERENCE SCENARIOS FOR USE IN MITIGATION ANALYSIS

Reference scenario type	Definition
No policy baselines	Accounts for the impact of climate and energy policies up to the base year (in terms of technological change and deployment) but assumes no climate policy beyond a certain point (usually 2010)
Current policy	Represents current implemented and planned climate and energy policies and extrapolates them into the future
Current ambition	Represents the implications of current policy ambitions such as Nationally Determined Contributions or midcentury strategies
Central mitigation scenario	A mitigation scenario that meets a given climate target with a central set of input parameters (for example, technology costs, availability, or both and extent of behavioral and societal change)

Source: Grant et al., “The appropriate use of reference scenarios in mitigation analysis,” *Nature Climate Change* 10 (2020), <https://www.nature.com/articles/s41558-020-0826-9>.

We are using two types of scenarios from this framework: the Reference scenario is a *No policy baseline* and the Central scenario is a *Central mitigation scenario*. As discussed below, we are not using a Current policy or Current ambition scenario in the main body of the paper.

The Reference scenario utilizes the Shared Socioeconomic Pathway 2 (SSP2), the middle-of-the-road scenario. Through the creation of Shared Policy Assumptions (SPAs), this scenario takes on key characteristics related to the original narrative for SSP2.²³ However, this scenario does not include current policies (climate, energy, or others) that might affect pathway outcomes beyond policies included in the 2015 baseline. Furthermore, the scenario is not coupled with a Representative Concentration Pathway (RCP) that would otherwise set a predetermined level of radiative forcing increase in 2100 over a pre-industrial baseline. Instead, the amount of radiative forcing is an output of the scenario and reaches 6.45 W/m2 in 2100, which has an associated global mean temperature rise of around 3.5° C. This temperature outcome is in the higher range of the 2.0° C to 3.6° C projected by the Climate Action Tracker but is lower than previous baseline projections of between 4.1° C and 4.8° C.²⁴ This outcome implies that the Reference is more closely associated with a no-policy scenario based on the definition outlined in Table TS1. However, this scenario does contain elements that change emissions drivers through assumptions about land and energy use developments that are built into the SSP framework as well as the 2015 policy baseline, resulting in a lower temperature outcome than previous no-policy baselines.

A no-policy scenario indicates missing information on progress achieved by current policy efforts, voluntary behavioral changes, and technological developments, to name a few factors. Today, certain geographies and sectors are progressing as climate-related policies seek to align emissions trajectories with mitigation pathways. For this reason, we do not rely on one individual assessment when informing philanthropic strategies. Instead, we incorporate multiple sources of information that also include assessments of current policies. This. reports comparison of the Reference and

Central scenarios (and comparison of those scenarios with the Ensemble) is therefore one step in a larger process, but nevertheless an important one that lays out a fuller spectrum of mitigation opportunities across multiple sectors and geographies — details that are often unavailable in other assessments.

We refer to the Reference and Central scenarios as anchoring scenarios because we use both as reference scenarios in different contexts. This is where the Ensemble comes into play. We examine scenarios that vary technological and behavioral elements. We then select parameters that best represent our programmatic narratives to create the Central scenario, but this does not mean we leave behind the wider set of scenarios. Instead, we use the entire Ensemble to evaluate trade-offs when informing strategies through sensitivity analysis. In such cases, the Central scenario becomes what Table TS1 refers to as a *Central mitigation scenario*, a type of reference scenario used as a comparator when asking what-if questions about the use of different technologies or pace of deployment.

What about other scenarios like current policy scenarios?

Some scenarios do not sufficiently cover all sectors, geographies, greenhouse gases, and land use sectors. The International Energy Agency (IEA) scenarios found in the World Energy Outlook (WEO) are a prime example. While very expansive, they focus mainly on energy, leaving out emissions associated with land use and agriculture. Furthermore, their focus is entirely on CO₂, and to a limited extent, methane, leaving out other greenhouse gases. Additionally, there are limitations on data access (within sectors and geographies). Even if limited use cases and comparisons with the energy data from the WEO are very useful, they need to be supplemented with additional assessments from other sources. Combining sources in such a bespoke way might result in the loss of a consistent narrative throughline across sectors and geographies.

The IPCC's most recent Assessment Report includes another example of a current policies scenario. The report incorporates current policies and ambitions, and in fact, the Illustrative Mitigation Pathway (IMP) used for the C7 Reference is a GCAM-based scenario.²⁵ GCAM was also used to evaluate a “current ambition” scenario in the *Science* article “Can updated climate pledges limit warming well below 2° C?”²⁶ This scenario models the intended emissions outcomes of updated Nationally Determined Contributions (NDCs) as part of the Paris Agreement. Importantly, neither the current ambition scenario nor the GCAM-based scenario are comprehensive representations of policies and pledges at the sectoral level. Instead, they take simplified approaches because NDCs often lack details about how targets might be met. China's NDC is to reach net-zero emissions by 2060, but details will emerge only in the country's five-year plans and other policymaking efforts. This paper on pledges is focused on the global result of achieving NDC targets. Its modeling does not incorporate sector-by-sector detail but instead relies on default modeling parameters to meet these targets. There is value in examining the outcome in the aggregate, but scenarios that leave out the *how* have few uses beyond the original question they sought to answer. Furthermore, such scenarios have a short shelf-life. For example, the IPCC assessment reports are published every six to seven years.

For now, we are limited to using no-policy or limited-policy Reference scenarios and Mitigation scenarios and to supplementing analysis with the use of bespoke current policy and current ambition scenarios.

Our scenario development process

With the aim of providing actionable insights from climate change mitigation pathways for philanthropic investments, we used a co-production method to solicit input through extensive engagement with analysts, experts, and scientists from JGCRI, the ClimateWorks Foundation, and its partners. This study's two anchoring scenarios (Reference and Central scenarios) and the accompanying Ensemble are an output of this co-production process and are used to inform programmatic strategies for philanthropic investments.

The broader climate change research community and the integrated assessment modeling community have worked together to develop numerous tools and frameworks with which to evaluate pathways to longer-term temperature outcomes. One such framework, the SSP-RCP Framework, blends the Shared Socioeconomic Pathways and the Representative Concentration Pathways into a matrix architecture.²⁷ This framework allows for a coherent assessment of pathways across models and scenarios because it provides a standardized set of concentration pathways (associated with temperature outcomes) and SSP narratives used as inputs for differentiating socio-economic futures. Evaluating the RCP-SSP Framework and the resulting scenarios from GCAM was the first step in a multi-year co-production process, followed by a more in-depth design of constraint analyses that inform modeling assumptions and choices (see the Comparison section below for visuals comparing the Ensemble to standard SSP-RCPs from GCAM).

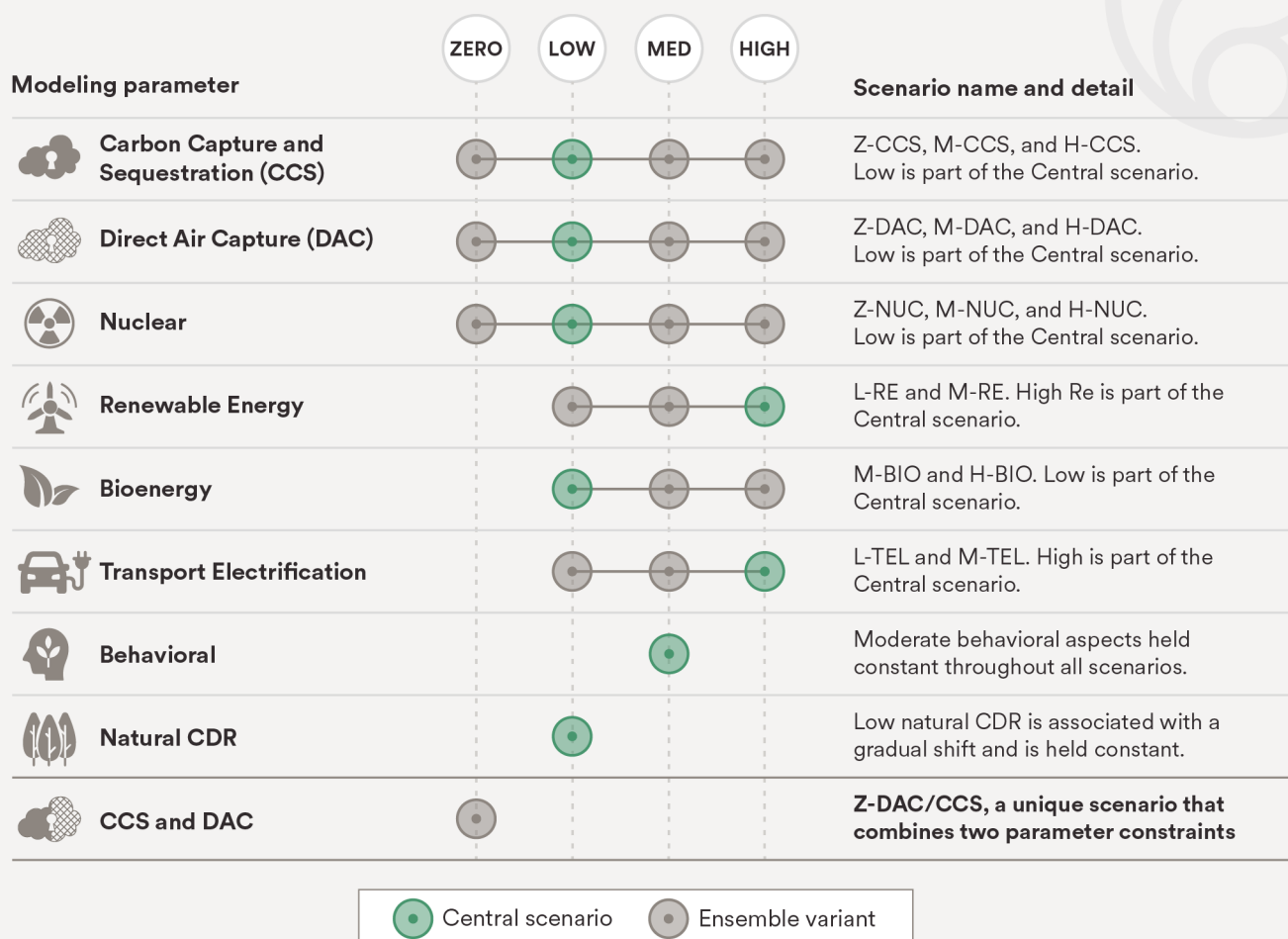
As a starting point, ClimateWorks uses SSP1 (the Sustainability Pathway) and RCP1.9 (which is associated with a high likelihood of limiting warming to 1.5° C by the end of the century).²⁸ Even so, the Central scenario (and accompanying Ensemble) builds on an SSP1-RCP1.9 scenario and can therefore be considered an SSP extension.²⁹ The Central and Ensemble scenarios can examine constraints that the original scenario cannot, and therefore they allow for further evaluation of trade-offs. The Central and Ensemble scenarios accelerate the pace of change to achieve net-zero carbon dioxide emissions by 2050. In this sense they are more ambitious than other scenarios with the notable exception of the Zero-CCS/DAC scenario.

To arrive at our constraint scenarios, we first examined and varied the availability and pace of change of key modeling components (or parameters) associated within the energy-land-water nexus. These components include the

- Pace and scale of land reallocation measures, including the use of reforestation and afforestation efforts;
- Scale of bioenergy production;
- Scale of behavioral shifts related to diets, shared transport and mode shifting, and energy use more broadly;
- Availability of carbon capture and storage (CCS) technologies;
- Availability of generating technologies like renewables and advanced nuclear energy options;
- Pace and scale of technological change (especially electrification) within end-use sectors;
- Use and scale of carbon dioxide removal technologies like bioenergy and carbon capture and sequestration (BECCS) and direct air capture (DAC).

By engaging with relevant parties and testing these key parameters, we developed a more tailored scenario, the Central scenario, which is closely aligned with many of our programmatic aims and which is described in the tables below. The Ensemble, which is a collection of 15 additional scenarios that vary key parameters, is also described in detail, alongside the Central scenario. Figure TS1, the teal circles indicate the parameter positioning for the Central scenario. Grey circles indicate the 15 Ensemble scenarios that isolate and vary constraints and incentives associated with parameters. For these Ensemble scenarios, all else is held equal. For example, a High CCS scenario releases the constraints on CCS of the Central scenario but retains all other constraints and incentives. (See the Detailed Assumptions section below for more details about how these scenarios were designed.)

TS 1: MODELING PARAMETERS FOR CENTRAL AND ENSEMBLE SCENARIOS



Importantly, two scenarios have a lower probability of achieving the 1.5° C outcome: the Z-DAC/CCS and the Z-DAC scenarios. See Figure 7 for details on temperature outcomes.

Detailed Assumptions

The Central Narrative

Through consultation with ClimateWorks program staff and experts in the field, we co-developed scenarios with staff scientists at JGCRI by evaluating programmatic aims and matching them with parameters within the GCAM model. Our starting point was an SSP1 Sustainable development pathway with an overarching aim of maintaining the end goal of limiting the global mean temperature increase by 2100 to 1.5° C, with very little overshoot. This goal is equivalent to that of a C1b scenario in the new lexicon of the IPCC AR6 Mitigation Report, to which our Central scenario pathway is compared below (see Figures TS7 and TS8). We then layered on sectoral aims based on the programmatic narratives of the work of ClimateWorks and our partners in the field. Themes emerged from engagement with ClimateWorks staff and partners, including an emphasis on the pathway co-benefits, rapid technological change, the maintenance of a thriving land use sector, and the potential contribution of lifestyle changes. The sectoral changes discussed here illustrate how these key themes are included within the Central scenario (Table TS2) and remain identical to the themes in our 2020 report. The Ensemble is discussed in the parameters section below where we explain how each narrative was translated into the modeling framework.

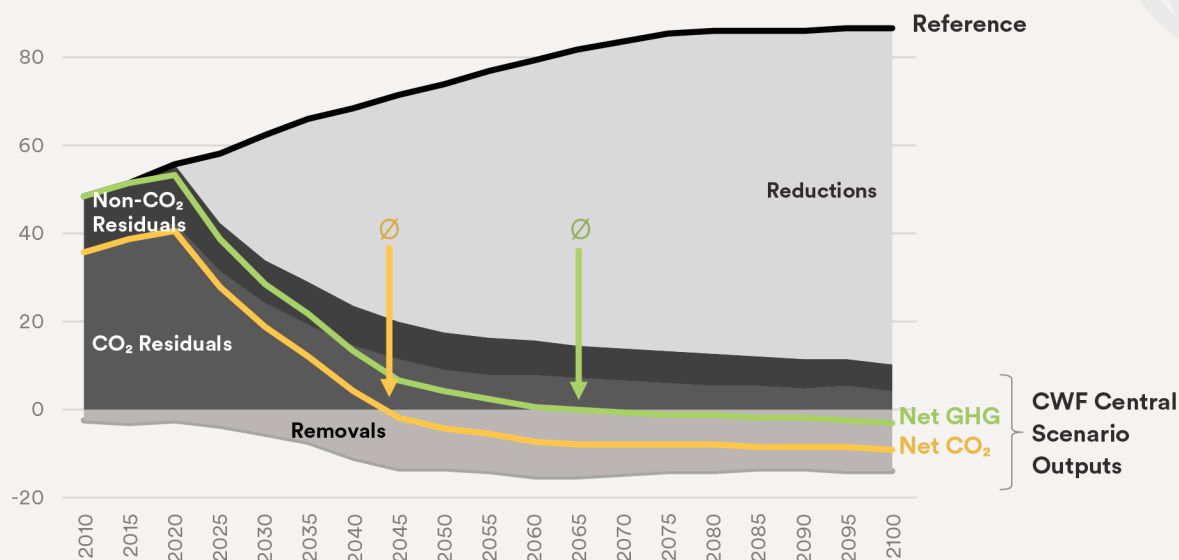
TABLE TS2. CENTRAL PATHWAY NARRATIVE AND SECTORAL DETAILS

Pathway Benefits	Technology	Sustainability	Lifestyle Contributions
The Central scenario seeks the many potential benefits of limiting global warming to 1.5° C. For example, it seeks to balance the use of land-based options and emphasizes the need for interventions that have multiple benefits.	The scenario underscores the importance of rapid technological deployment, and especially electrification wherever possible, to utilize a future zero-carbon grid. Meanwhile, the deployment of efficiency measures allows space for the scaling of sustainably sourced bioenergy and other zero-emission alternative fuel use where electricity is not available.	The scenario highlights the importance of maintaining a thriving land-use sector that aids in climate stabilization without sacrificing biodiversity. This goal implies a gradual ramping up of changes to farmlands, forests, and other natural habitats. To emphasize the importance of scaling sustainable land use practices, a constraint is placed on the total amount of available bioenergy.	The scenario highlights the capacity of human behavior to change. Dietary and other consumption pattern shifts align with a future that focuses on sustainable development instead of business as usual.
Electricity	Fuel Supply	Industry	
The power sector is used as an engine of decarbonization. As it rapidly reaches net-zero emissions by midcentury, the electrification of end uses is widely deployed. Large amounts of renewable generation come online and the existing generation fleet is retrofitted to bring on zero-carbon sources of electricity. These rapid transitions allow near-term and sustainable emissions reductions.	Fuel supply, or the extraction, processing, and distribution of fossil fuels (coal, oil, and gas) and alternative fuels like hydrogen and bioenergy play an important role in reducing emissions both as a result of demand-side measurements in end-use Sectors, but also via changes in practices in upstream/ midstream processes. Technological innovations offer emissions reduction potential during this “messy middle,” during which renewables and electrification require time to scale.	The industrial sectors see reduced emissions from the deployment of efficiency measures and the transition to electricity and alternative fuels, including bioenergy and other alternative zero-carbon fuels like hydrogen. Demand is reduced both due to behavioral changes upstream and reduced materials demand as a result of the adoption of more sustainable design approaches and material recycling.	
Buildings	Transport	Agriculture	
The buildings sector sees widespread deployment of electrification across all end uses. Efficiency measures curb energy demand. Homes get smaller. Finally, F-gases, a powerful GHG used in space cooling, are curbed by accelerating the pace of the phase-down envisioned in the Kigali Amendment to the Montreal Protocol.	Road transport, both passenger and freight, electrifies rapidly. Further mode shifting to public and shared services allows for better use of fleets. Meanwhile, demand and efficiency measures curb emissions in the aviation and shipping sectors.	The agricultural sector seeks increased crop yields while adopting less emissions-intensive practices in the cultivation of crops like rice. An emphasis on plant-based proteins significantly reduces methane from animals and pastureland is reallocated for other uses. Bioenergy is constrained, reducing competition for prime croplands.	
Forest & Land Use	Super Pollutants	Carbon Dioxide Removal	
A near-term halt to deforestation is followed by a slow increase in reforestation that almost fully reverses forest and land use trends of the last half-century. A cap on total bioenergy lessens pressure on food prices and availability, and yet, unused pasturelands and other marginal or less productive land sources are reallocated to food cultivation.	Super pollutant emissions, or non-CO₂ GHGs, are significantly reduced because of changing activity in the land and energy sectors and independent, concentrated mitigation efforts (i.e., the Kigali Amendment and gas leak reductions). Benefits accrue for human health as well as the climate.	Carbon dioxide removal, both natural and technological, becomes a backstop for residual emissions and emissions from hard-to-decarbonize sectors. Due to uncertainties about the amount of carbon that can be reduced, the Central scenario relies on multiple CDR measures, assumes these measures are introduced gradually, and highlights the increasing scale of inaction's consequences.	

In addition to reflecting the narratives of each sector and the goal of limiting the overshoot of 1.5° C (for compliance with the C1b scenario in the IPCC AR6 report), we targeted net-zero carbon dioxide emissions by midcentury. This midcentury goal masks the fact that sectors achieve emissions reductions at different times. Consequently, at the global level, the Central scenario reaches net-zero CO₂ emissions closer to 2045 and net-zero GHG emissions near 2065 (see Figure TS2). Net CO₂ emissions hover around -7 GtCO₂ throughout the second half of the century, with annual removals totaling between 10 GtCO₂ and 12 GtCO₂ and annual residual emissions totaling between 3 GtCO₂ and 5 GtCO₂. Meanwhile, net GHG (measured as CO₂e) totals do not exceed a removal total of 3 GtCO₂e in the second half of the century. Non-CO₂ residuals total between 7 GtCO₂ and 10 GtCO₂e, depending on the year.

TS 2: NET-ZERO BALANCING EMISSIONS

Projections and 1.5° C scenario of global greenhouse gas emissions (GtCO₂e/yr)



Net zero for either CO₂ or total GHG is achieved when residual or produced emissions are balanced by negative emissions through CDR. In the Central scenario, net zero CO₂ is achieved between 2045 to 2050 while net-zero GHG is achieved closer to 2065.

Parameters and Ensemble assumptions

In the table below, we describe the parameter adjustments used to create the Central scenario. We simplify those adjustments as follows:

- Coefficient adjustment that simulates a change in technological preference within a sector/subsector,
- Quantity adjustment that constrains or limits a key parameter by a set threshold,
- Price adjustment that simulates a demand response from either an incentive or disincentive, and
- Productivity adjustment that simulates a change in service provision per unit of input (e.g., materials, energy, land, etc.).

We also provide descriptions of the desired outcomes of the parameter changes and whether a given parameter was used as a step change from the original SSP1 or whether it is aligned with SSP1 default assumptions. Parameter adjustments have practical policy implications because they align sectors and geographies with a globally consistent mitigation pathway. In many cases, the adjustment of one parameter impacts multiple sectors due to the integrated nature of the modeling environment. For example, a quantity adjustment that constrains the total amount of bioenergy production available will affect both the land and energy sectors. The interaction of parameters makes it important to consider overlapping systems in policy design.

Many of the parameters were created through the co-production process with expert input, but two key external reports were crucial in the design of the scenario:

- The Netherlands Environmental Assessment Agency's alternative pathways to 1.5° C exploratory scenarios using the integrated assessment model IMAGE. The Lifestyle Change and Low Non-CO₂ scenarios from this exercise were extensively used.³⁰
- The Low Energy Demand (LED) scenario using the integrated assessment model MESSAGE by the International Institute for Applied Systems Analysis.³¹

The Table TS 3 details how these details how these parameters were used to create the Ensemble.

TABLE TS3: KEY SCENARIO PARAMETERS AND COMPARISON TO SSP1, THE SUSTAINABILITY PATHWAY

Sector	Category	Parameter change type	Aim of parameter change	Is the parameter a step change, or is it aligned with SSP1?
 Electricity	High Renewable	Price adjustment: Lower capital and operating costs	Sustained price reductions increase the share of wind and solar generation, allowing renewables to dominate electricity generation	Step change
	Low nuclear	Price adjustment: No reductions to capital and operating costs	Price for nuclear power remains a barrier to scaling, but with the pace of change in total emissions, nuclear generation grows in the next 2–3 decades	Step change
	Low CCS	Price and quantity adjustment: No offshore CCS and no cost reductions	CCS is used as a temporary stopgap measure because growth is not sustained through to 2100. Instead, renewable energy dominates electricity generation after midcentury	Step change
	Low bioenergy	Quantity adjustment: Total bioenergy production cap	With constrained supply, BECCS-related generation remains low, lessening the burden on land use sectors	Step change
 Fuel Supply	Reduced methane leakage	Productivity adjustment: Methane leakage rates	25% further reduction in comparison to SSP1	Step change
	Limited bioenergy	Quantity adjustment: Capped at 150 EJ linear increase from 2030 to 2100	By limiting the total amount of bioenergy production, use of bioenergy across many sectors, including use of BECCS, is curtailed. The many integrated effects include reduced competition within land use sectors	Step change
 Industry	Electrification	Price adjustment: Generalized through coefficient preferences	Incentivize fuel switching to benefit from rapid decarbonization of the electricity sector	Aligned
	Efficient cement	Quantity adjustment: Cement/clinker ratio raised to ~2/3	Reduced clinker lowers the carbon intensity of production and changes the material input	Aligned
	Lowered cement demand	Quantity adjustment: Income elasticity	Reduced home sizes, lengthened building lifetimes, and an emphasis on public transit results in a 45% reduction in cement demand by 2100	Aligned
	Reduced industry output demand	Quantity adjustment: Income elasticity	Simulates moderate adoption of circular approaches and lowered material demand from end-use sectors, including transport and buildings	Step change
	Improved efficiency of other industries	Productivity adjustment: 10% more than SSP1 by 2050 and 20% more by 2100	Simulates scaled investment in efficiency, resulting in reduced energy use	Step change
	Reduced feedstock use	Productivity adjustment: Lowered coal and petrochemical preference	Simulates reduced demand for petrochemical products by raising the preference for alternative feedstocks, including bio-based feedstocks	Step change

 Buildings	Smaller buildings	Quantity adjustment: Satiation demand function	Dampens trend toward larger per capita floorspace in residential buildings	Step change
	Heating and cooling efficiency	Productivity adjustment: SSP1 achievements met by 2050	Achieves 2100 SSP1 levels of deployment in 2050, simulating rapid deployment of energy efficiency and fuel switching	Step change
	F-gas reduction	Productivity adjustment: Sets global marginal abatement costs	Achieves a more rapid phase down of F-gas use in cooling-related technologies. Pricing in Global South are matched to the less expensive Global North, simulating technological transfer allowing for uniform and steep reductions irrespective of geography.	Step change
	Household energy consumption	Productivity adjustment: Demand response	Appliances and general plug load to simulate deployment of efficient appliances and better building design	Step change
 Transport	Ridesharing	Productivity adjustment: Load factors for 4-wheel, light duty vehicles (LDV) increased	Simulates sustained adoption of ridesharing business models that intensify vehicle use and lower fleet size	Step change
	Transit preference	Price adjustment: Value of Time Traveled (VOTT) changed	Public transit is preferred over private transportation, allowing for larger transit fleets with lowered emissions intensity	Aligned
	LDV demand reduction	Quantity adjustment: Response to above functions on demand	Lowered overall use of private vehicles due to preference for public transit and demand shift to shared transport lowers total demand for LDV transportation	Aligned
	LDV electrification	Quantitative constraint and price adjustment: Share weights for new sales reach 100% by 2050	Simulates ambitious scaling of electric vehicles (fuel cell and battery electric), linked to a decarbonized electricity grid	Step change
	Rail electrification	Coefficient adjustment: Share weights for new sales reach 100% by 2100	Simulates ambitious scaling of electric rail linked to a decarbonized electricity grid	Step change
	Freight electrification	Coefficient adjustment: Share weights new sales reach 100% by 2060	Simulates ambitious scaling of electric vehicles across all classes of vehicles linked to a decarbonized grid	Step change
	Demand reduction for Aviation and Shipping	Quantity adjustment: Income elasticity adjustments	Lowers demand for aviation and movement of goods through shipping by around 30%. Mode shift to other forms of freight and transit	Step change
	Reduced non-CO2 in shipping	Quantity adjustments: Response to above changes	Largely a result of demand reduction but also fuel switching away from dirtier bunker fuels	Step change
 Agriculture	Limited meat consumption	Coefficient adjustment: Reduced preference for animal proteins	Simulates global dietary shift away from emissions-intensive meat consumption toward plant-based protein	Step change
	Healthier diets	Quantity adjustment: Reduction in income elasticity for non-staples	Improved diets, focus on staples, and reduction in non-staples like meat, dairy, sheep/goat/poultry lower sugar consumption	Step change
	Increased crop yields	Productivity adjustment: Technology improvements rates increased	Technological improvements with sustained trends in most crops while rice cultivation sees large changeover in practices that reduce overall production below SSP1	Aligned
	Reduced methane and N2O emissions from agriculture, meat, and dairy	Productivity adjustment: Technology improvement rates increased	Better agriculture practices in rice cultivation, feed changes for ruminant animals, additives for improving enteric fermentation, improved forage quality and concentration, and better animal breeding practices	Step change
 Forest	Gradual afforestation	Price adjustment and coordination on timing	Simulates a slower changeover of afforestation to represent implementation difficulties and limiting of monocropping in favor of maintaining biodiversity	Step change

TABLE TS4. MODELING PARAMETERS AND DETAILED DESCRIPTIONS OF ZERO, LOW, MEDIUM, AND HIGH ASPECTS OF ENSEMBLE SCENARIOS

Modeling parameter	Zero	Low	Medium	High
Carbon Capture and Sequestration (CCS)	No CCS; relatively infinite cost of CCS storage	CCS costs are 10X SSP2 assumptions	Regular SSP2 assumptions	CCS costs are 20% lower than SSP2 assumptions
Direct Air Capture	No DAC technology is available	DAC is limited to a level of 5 GtCO ₂	DAC is limited to 10 GtCO ₂	No DAC constraint
		DAC has lower preference over other abatement technologies, and gradually rises to equal preference by 2050	Equal preference as other abatement technologies	Equal preference as other abatement technologies
Nuclear	No new nuclear power installation starting 2020, i.e., zero preference	Capital costs for nuclear generation do not reduce; nuclear generation is less preferred option starting 2020, only 25% as preferred as equal priced alternatives; preference for nuclear reduces linearly to 0 preference by 2100	Regular SSP2 assumptions	Advanced nuclear (Gen III) capital costs decline by approx. 2% every 5 years
Renewable Generation		Wind power capital costs fall at constant rate of 1% every 5 years	Regular SSP2 assumptions	Wind power capital costs fall at a higher rate initially, starting at 7% every 5 years to 0.1% decrease by 2100
		Solar power capital costs fall at about 5% every 5-year period initially, gradually slowing down to 0.1% by 2100; overall, capital costs for solar fall by 25% by 2100; capital costs for PV storage fall by 15% by 2100	Regular SSP2 assumptions	Solar power costs fall significantly, starting at 14% in 5-year period 2020–25, and then gradually by 2100; overall, capital costs of solar fall by 50% by 2100; capital cost of PV storage falls by 40% by 2100
		Capital costs for geothermal power remain constant	Regular SSP2 assumptions	Capital costs for geothermal power reduce by 25% until 2100
		Renewable energy has equal preference to other sources by 2040	Regular SSP2 assumptions	Renewables are as equally preferred as other options, starting in 2020, i.e., the choice between generation options is purely based on costs
Bioenergy		Linear constraint from 2020, limited to 100 EJ in 2100	Linear constraint from 2020, limited to 120EJ in 2050 and to a slower increase from 2050 to 2100; limited to 150 EJ in 2100	Unconstrained
Electrification of Transport		Preference for electric cars and trucks increases gradually and equals that for fossil fuel options only by 2100	Electric cars/trucks are gradually 2.5 times as preferred over fossil fuel options	Electric cars/trucks are 2.5 times as preferred as fossil fuel options in 2100; preference for fossil fuel options reduces gradually and no fossil fuel cars/trucks are sold after 2050

Sectors and subsector levers discussion

There are numerous ways in which data at the geographic, sector, and subsector levels might be aggregated or disaggregated. For example, there are 32 geographies within GCAM, but we chose to aggregate them into 10. Similarly, we chose to aggregate energy and land-related sectors and subsectors from GCAM into seven key sectors with two cross-sectoral categories (CDR and super pollutants). To be clear, these simplifications are choices meant to help in the process of communicating results. We attempted to showcase a few key subsectors for each of the seven sectors that align with programmatic areas of focus within climate philanthropy. Table TS5 describes each of these subsectors and the mitigations levers that apply within them. In future work, we intend to dive deeper into these sectors to further discuss transition strategies, opportunities, interdependencies, and temporal aspects.

TABLE TS5: SUBSECTOR AND MITIGATION DETAIL

Emissions sector/ Subsector	Subsector description	Mitigation demonstrated in scenario
 Electricity	~26% of global emissions in 2020	Represents emissions from generating electricity across multiple technologies
 Coal	Thermal coal generation dominates emissions in this sector at around three-fourths of emissions in 2020, making it the largest single subsector.	Traditional fossil thermal generation from fossil fuels are replaced with renewable and/or zero-carbon technologies; GCAM includes 30 generating technologies, including use of carbon capture and sequestration technologies; the latter are constrained in the model, but ultimately are used in the medium term to reach zero carbon emissions intensity globally by 2045; thereafter, renewable generating technologies are scaled further, reducing use of CCS technologies; ultimately, this scenario demonstrates the benefits of a fully net-zero emissions intensity grid as electrification across end uses scales throughout the time period
 Gas	Use of natural gas is less carbon-intensive than coal generation, but ultimately needs to be phased out to reach a zero-carbon grid by midcentury.	
 Liquids	Liquids consist of a mix of oil and biofuels. Though smaller than the above fuels, this subsector remains a large source of emissions.	
 Biomass	Counted within the modeling framework as carbon neutral, biomass when coupled with CCS, becomes a negative emissions technology.	Coupling generation with biomass and CCS (BECCS) allows for balancing produced emissions that remain on the grid. By 2050, traditional thermal generation is negligible. Use of BECCS allows the grid to have a net-negative emissions intensity. Though BECCS might not be the ultimate CDR technology of choice, used in this way, it allows us to demonstrate the balancing nature of CDR technologies given persistent residual emissions. Bioenergy is constrained in this scenario (see fuel supply below).
 Fuel Supply	~8% of global emissions in 2020	Represents emissions from extraction, processing, refinement, and distribution of fuels including oil, gas, and coal but also energy related to production of hydrogen and biofuels
 Coal	Made up of coalbed methane due to release of gas during mining operations.	The scenario simulates the benefits of fuel switching in end uses (especially electrification and generation focused on renewables) because it results in demand-related reductions across all fossil fuels. Further reduction opportunities exist in cleanup, plugging, and capturing methane leaks from extraction operations across all fuels. A combination of fuel switching, efficiency, and carbon capture and sequestration in refining reduces emissions further (enhanced oil recovery is included here).
 Oil	Made up of methane related to venting and leakages during extraction and transport and energy-related emissions from refinement processes.	
 Gas	Made up of methane due to leaks in extraction, processing, and transportation of natural gas.	
 Other	Energy-related emissions from production and processing of hydrogen, bioenergy, and other alternative fuels.	Such fuels are less carbon-intensive than their fossil fuel counterparts, but efficiency improvements, electrification, and limited use of CCS in processing/refinement allows for additional reductions. In the case of bioenergy, process can become a negative emissions technology when CCS is used, though this possibility is limited in the scenario by the cap placed on bioenergy. Scaling of these alternative fuels allows low-emissions alternatives in end-use sectors that are harder to electrify, including high-heat industries, shipping, and aviation. While this scenario highly constrains the amount of bioenergy and optimizes its use in the power sector, another logical allocation of these resources in is providing fuel for direct use in these sectors, which account for the residual emissions of midcentury.

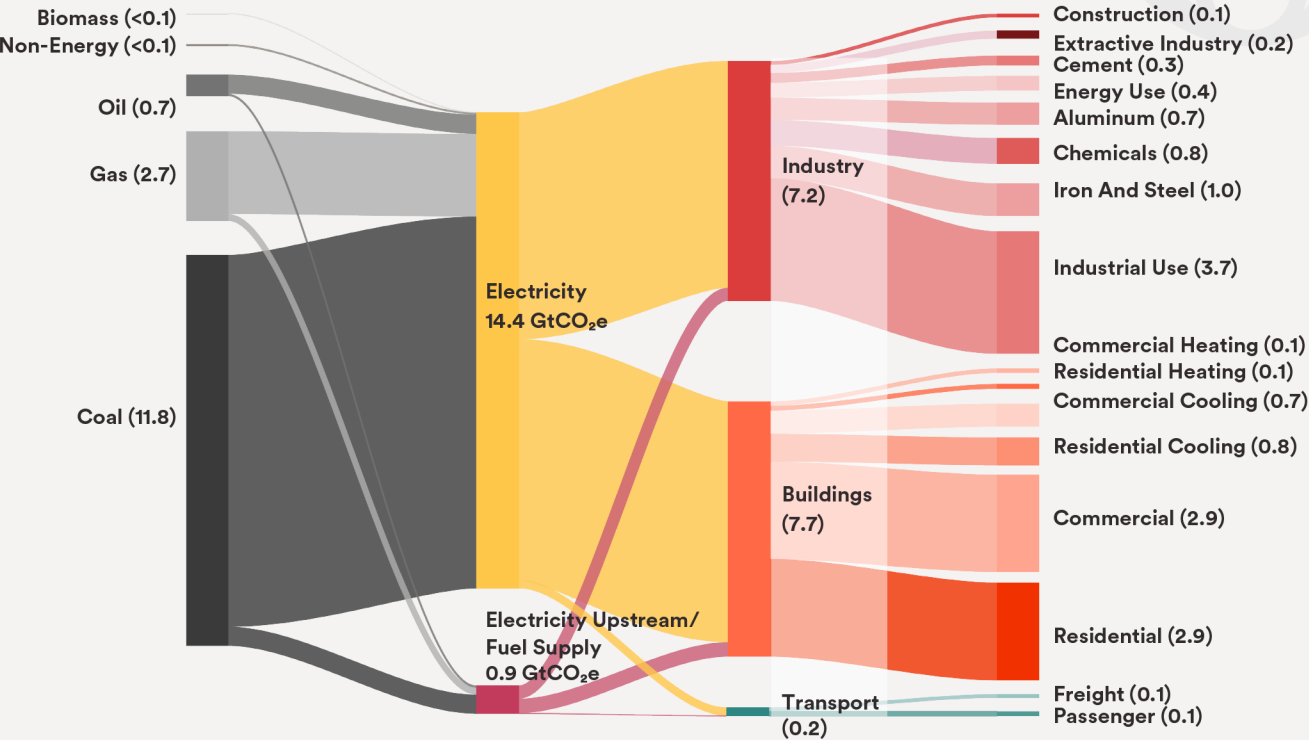
 Industry	~23% of global emissions (direct) in 2020	Represents energy, process, and waste-related emissions in industrial end-use sectors
 Energy Use	Energy use for all industry in all other subsectors represented below. Outputs of the aggregate industrial sector are represented in generic terms.	Due to the high aggregation within this sector, mitigation efforts are limited to generic mitigation levers like fuel switching and deployment of efficiency measures.
 Agricultural Energy	Energy related to emissions within the agricultural sector (stationary and mobile)	For stationary emission sources, mitigation options include fuel switch to electrification, efficiency, and materials demand reductions. For mobile sources, mitigation options include fuel switch to electrification and hydrogen use.
 Aluminum	Energy-related emissions for alumina production and aluminum processing	Options for mitigation include energy efficiency, fuel switching, and use of CCS. Because aluminum processing is already largely electrified, options include efficiency and use of zero-emissions electricity. Demand reductions are also an option.
 Cement	Energy- and process-related emissions for cement production	Mitigation options include fuel switch to electrification, use of CCS technologies, efficiency, and materials demand reductions.
 Chemicals	Energy-related emissions and those associated with feedstocks	Mitigation options include fuel switch to electrification, use of CCS technologies, efficiency, and materials demand reductions.
 Construction	Represents mobile, stationary, and feedstocks	Mitigation options include fuel switch to electrification, efficiency measures, and materials demand reductions.
 Feedstocks	Chemical-related inputs to industrial sector, primarily from oil but also from coal and biomass	Demand reduction and materials switching away from petroleum-based inputs allows for feedstock-related emissions reductions. Small amounts of feedstocks come from non-petroleum sources like coal used in steel-making processes, but these inputs are regionally specific. Bio-based inputs are lower-emissions alternatives to fossil-based feedstocks, but due to land-use competition, the use of bio-based products must be weighed against alternative uses for land.
 Fertilizer	Represents energy and process-related emissions associated with fertilizer production	Mitigation options include fuel switch to electrification, use of CCS technologies, efficiency, and demand reductions through changes in farming practices away from high levels of fertilizer use.
 Iron and Steel	Includes energy- and process-related emissions from multiple production types (blast furnace, EAF with scrap, and EAF with DRI)	Mitigation options include fuel switch to electrification or hydrogen, use of CCS technologies, efficiency, and materials demand reductions.
 Mining Energy	Energy related to energy use within the mining and extractive sectors (stationary and mobile)	For stationary emission sources, mitigation options include fuel switch to electrification, efficiency, and materials demand reductions. For mobile sources, mitigation options include fuel switch to electrification and hydrogen use.
 Processes	Industrial process emissions here refer to waste and are made up mostly of super-pollutant non-CO2 gases.	Emission sources include HFC production, foams, nitric acid production, industrial solvents, semiconductor industry, adipic acid, and the aluminum industry. Mitigation options include switching to materials that do not use products with HFCs.
 Buildings	~11% of global emissions (direct) in 2020	Represents direct fuel use and associated super-pollutant emissions in buildings sector for heating, cooling, other for both residential and commercial buildings
 Cooling	Super-pollutant emissions related to use of F-gases in cooling are expected to quadruple by 2050 as cooling demand grows in developing countries.	Options for reducing F-gas use for space cooling and refrigeration include deployment of appliance efficiency, cool roofs, retrofits to building envelopes, and adoption of substances with relatively low global warming potential. Use of alternatives to f-gases limits the leakage of these gases over the lifetime of the appliances as well as end-of-life releases.
 Heating	Made up space heating technologies ranging from burning of traditional biomass to combustion of fossil fuels	Mitigation options include efficiency deployment coupled with a switch from traditional biomass and coal to electrification. Slow retrofit turnover of furnaces means that electrification is an opportunity area well into second half of the century.
 Other	Refers to plug load from appliances, water heating, and clothes dryers	Mitigation options include efficiency deployment and switching away from fossil fuels for water heating and clothes drying.
 Process/Waste	Refers to municipal solid waste and wastewater and to some F-gases related to poor disposal practices	Mitigation options include adoption of circular economy approaches for material recovery from products, adoption of F-gas disposal regulations, switching away HFCs in aerosols, solvents, and fire extinguishers. Deployment of methane capture from waste streams reduces methane from MSP and wastewater.

 Transport	~15% of global emissions (direct) in 2020	Represents direct emissions related to passenger and freight transportation on road, rail, aviation, and marine shipping modes
 Passenger (Land)	Refers to all passenger vehicles used on land, including light duty vehicles, two-wheelers, three-wheelers, SUVs, trucks, buses, and trains. The GCAM model has wide coverage across vehicle types and can simulate demand changes and fuel switching in a wide array of options.	Levers are wide-ranging in this sector and include technological components like efficiency and switching to electrification, but also behavioral components like shifting from private to public transit and ride sharing.
 Freight (Land)	Refers to a wide variety of trucks as well as to train freight	There are wide-ranging options, given the large variety of truck classes and uses. Electrification is the main driver of emissions reduction in this sector, but efficiency gains are deployed because electrification takes time to scale.
 Shipping	Refers to domestic and interregional shipping of goods	Demand reduction, efficiency and switching away from bunker fuels are key mitigation levers in this subsector.
 Aviation	Refers to both domestic and interregional travel of people and goods	Demand reduction, efficiency, and switching to lower-carbon-content fuels drive emissions reduction in this sector. Biofuels is a key component in this sector, but research on alternative fuels and electrification might change the outlook for this sector in future research.
 Forests And Land Use	Large uncertainty but likely ~6% of global emissions in 2020	Represents carbon dioxide-related emissions from all land types, including managed/unmanaged forests, farmlands, and tundra and other marginal lands.
 Land Use Transition	Refers to allocation of land type and associated emissions. Land use is fully integrated across many land types and can be simplified into crops (multiple), dedicated biomass, forest (managed and unmanaged), grasslands, other natural (multiple), other arable, pastureland (multiple), shrubland, and urban.	There are many mitigation levers within land use, including reforestation, afforestation, agroforestry, crop intensification, changes to agricultural practices, dietary shifts (reduced meat consumption), biomass production, and regenerative agriculture. Owing to the complexity of the interactions between land use and energy systems, this sector is simplified into net emissions accounting, but more information on land use allocation and associated emissions is available.
 Agriculture	~12% of global emissions in 2020	Represents direct emissions associated with the production of food
 Meat and Dairy	Refers to all animal meat production and associated dairy production	All meat production is associated with some level of emissions but there is a wide variation; beef and dairy production are most emissions intensive. Mitigation options include demand reduction through outright lowered meat consumption and switching to plant-based proteins. Reduction in meat consumption frees up large amounts of land that can then be reallocated to crop production, biomass production, or natural CDR options like reforestation/afforestation.
 Crops	Refers to direct emissions related to crop production across multiple classes of crops	Rice cultivation is the main source of emissions in this sector because it produces methane. Switching from wet to dry rice cultivation lowers the amount of methane produced. Crop intensification and use of regenerative agriculture both contribute to natural CDR as well as free up land for bioenergy and other natural CDR options like reforestation/afforestation.

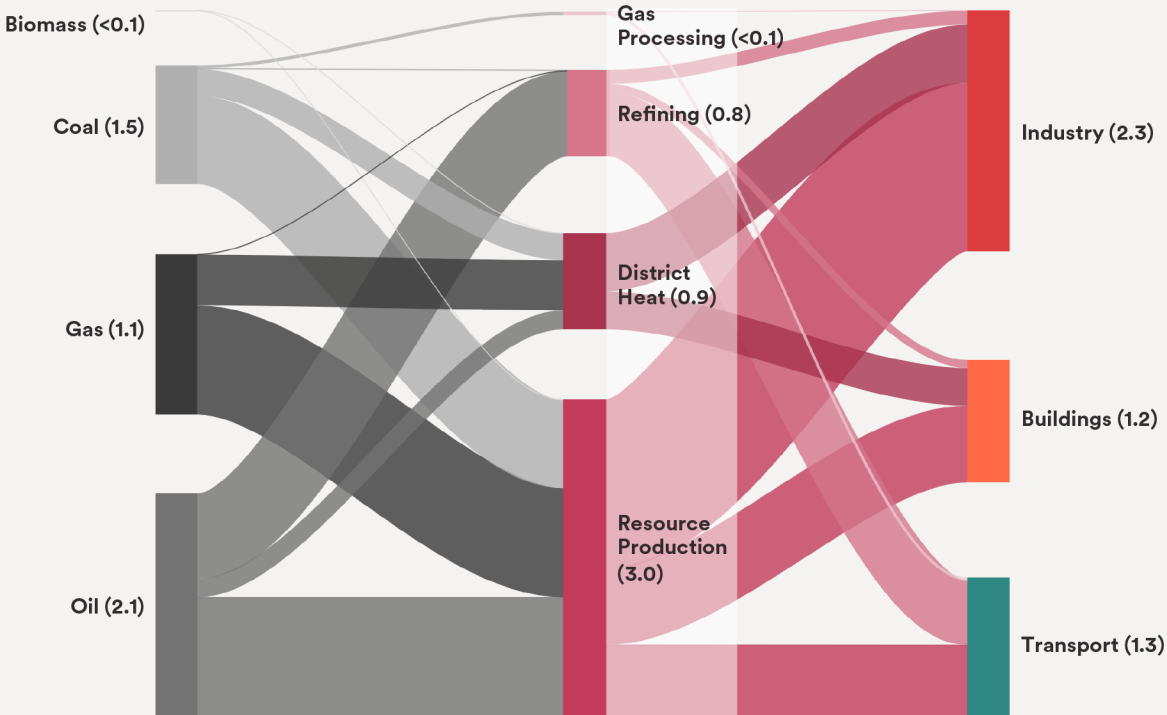
Sector and subsector current emissions

TS 3: 2020 ELECTRICITY AND FUEL SUPPLY EMISSIONS FLOW

Electricity
(14.4 GtCO₂e direct, 0.9 GtCO₂e indirect, 26% of total emissions in 2020)



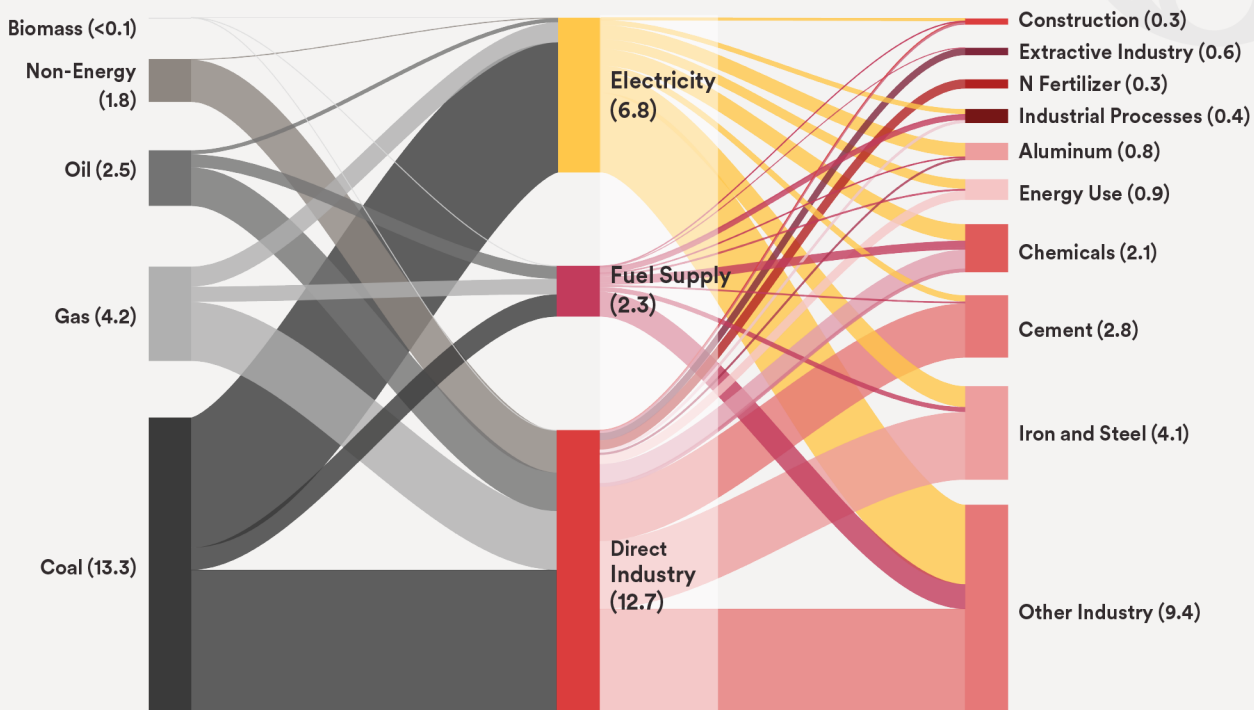
Fuel supply
(4.7 GtCO₂e, 8% of total emissions in 2020)



TS 4: 2020 INDUSTRY AND BUILDINGS EMISSIONS FLOW

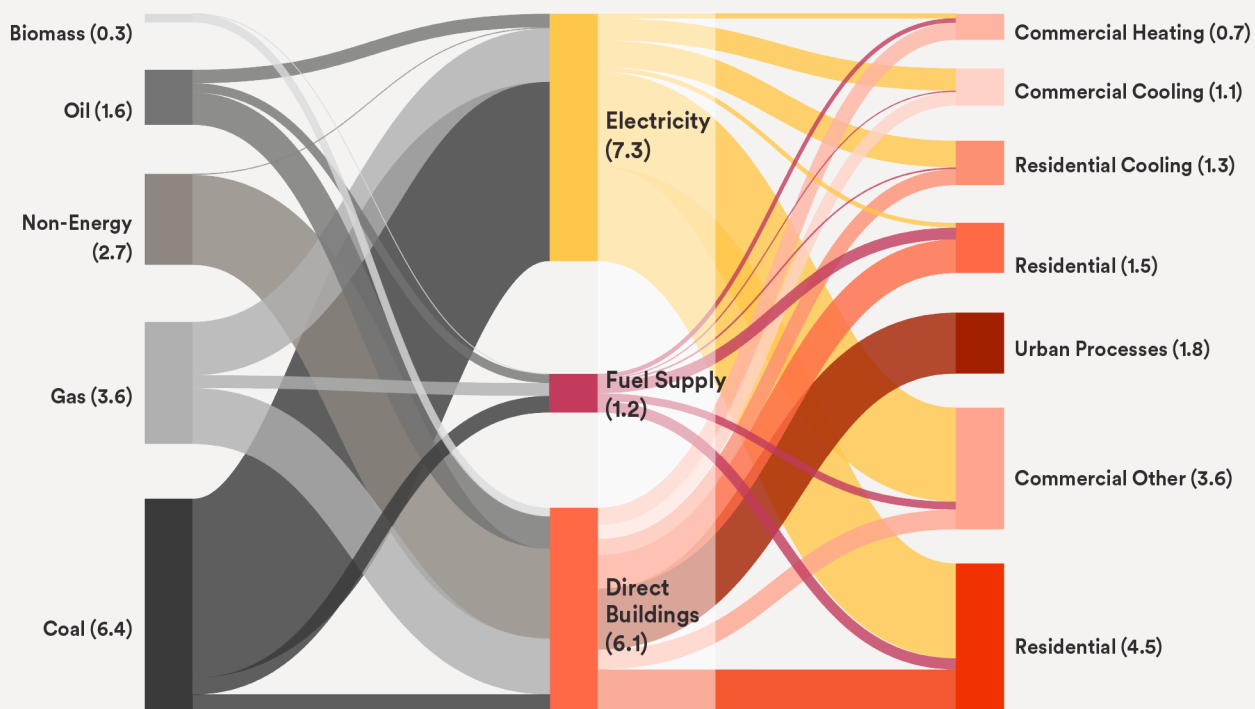
Industry

(21.8 GtCO₂e of associated emissions, 23% of emissions in 2020)



Buildings

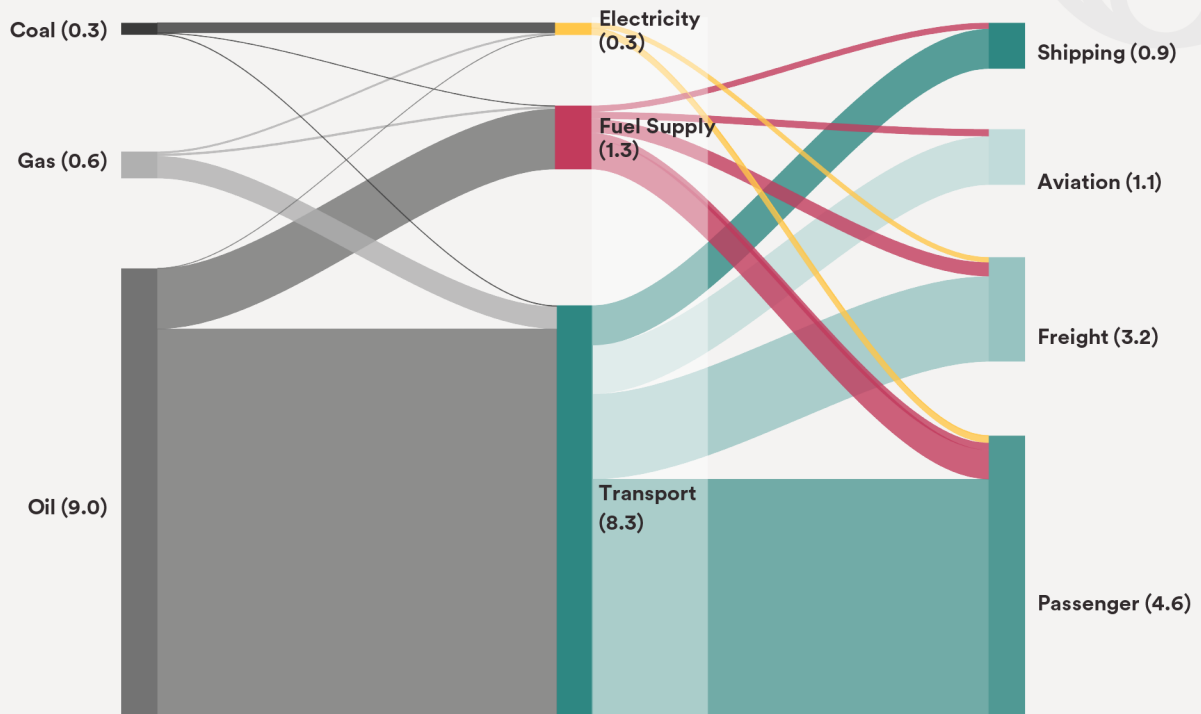
(14.5 GtCO₂e of associated emissions, 11% of emissions in 2020)



TS 5: 2020 TRANSPORTATION AND AGRICULTURE EMISSIONS FLOW

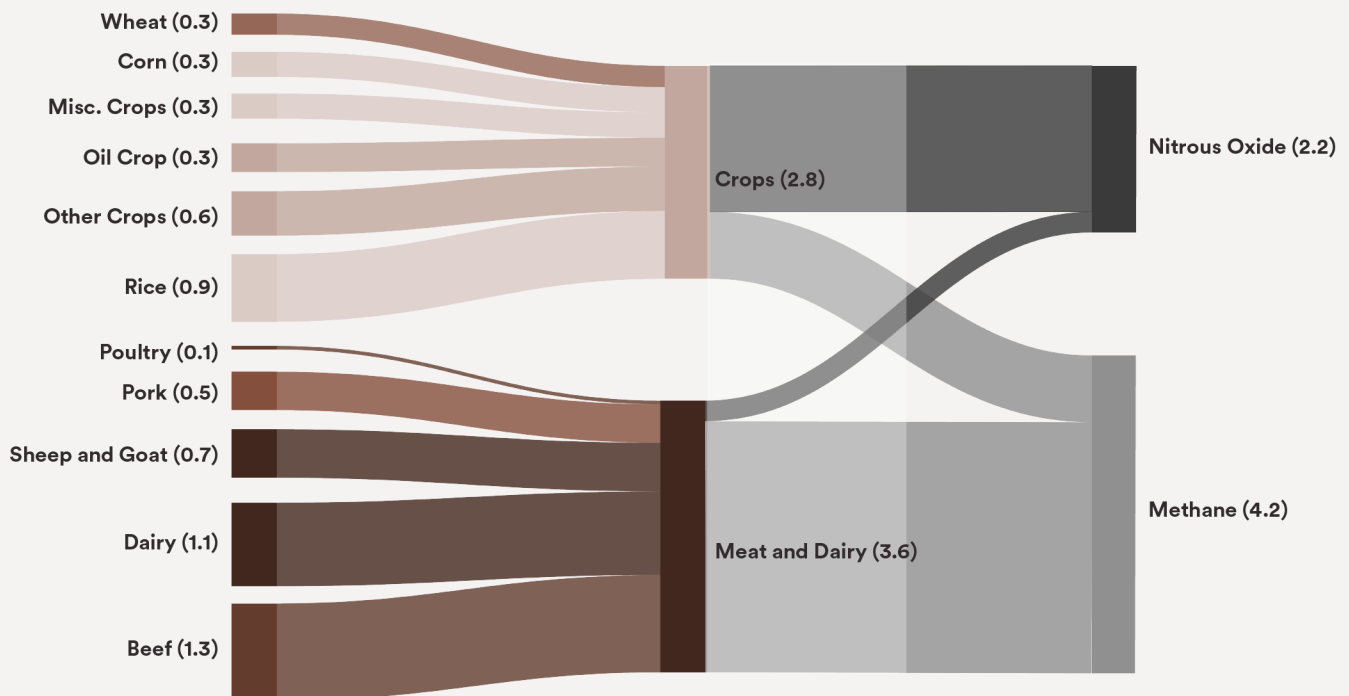
Transportation

(9.9 GtCO₂e of associated emissions , 15% of emissions in 2020)



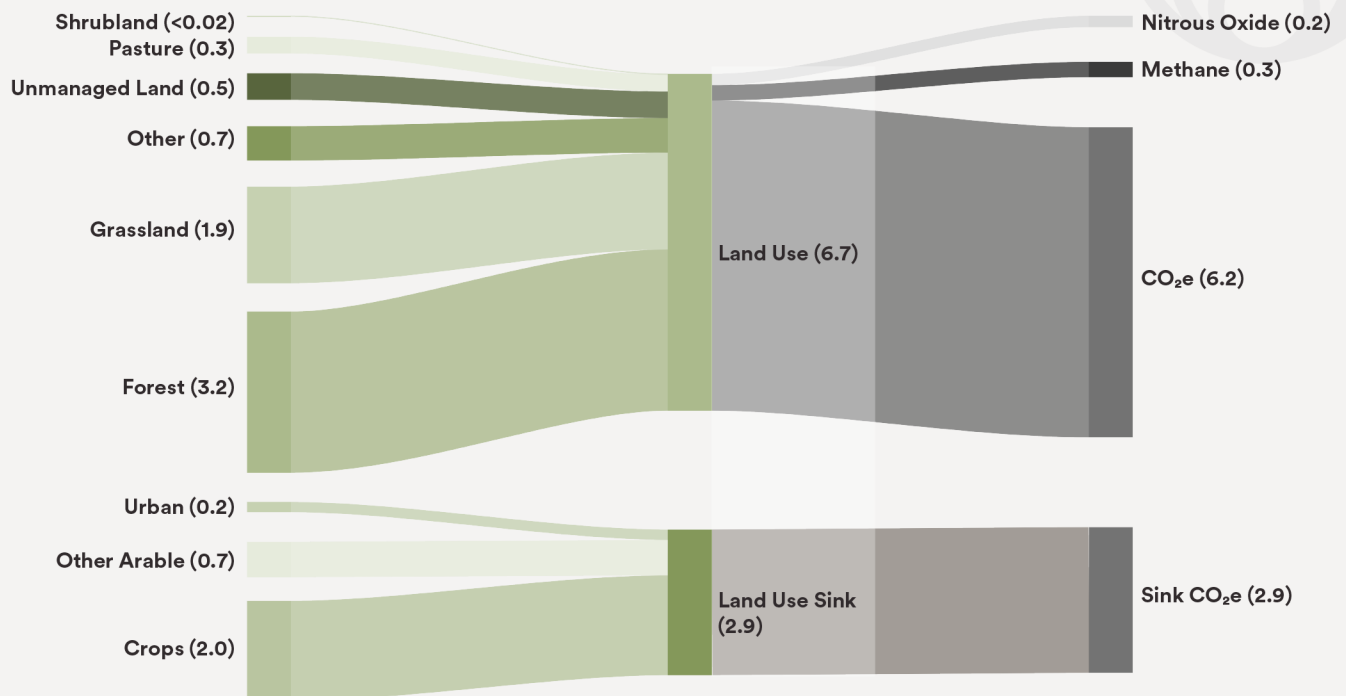
Agriculture

(6.4 GtCO₂e, 12% of emissions in 2020)



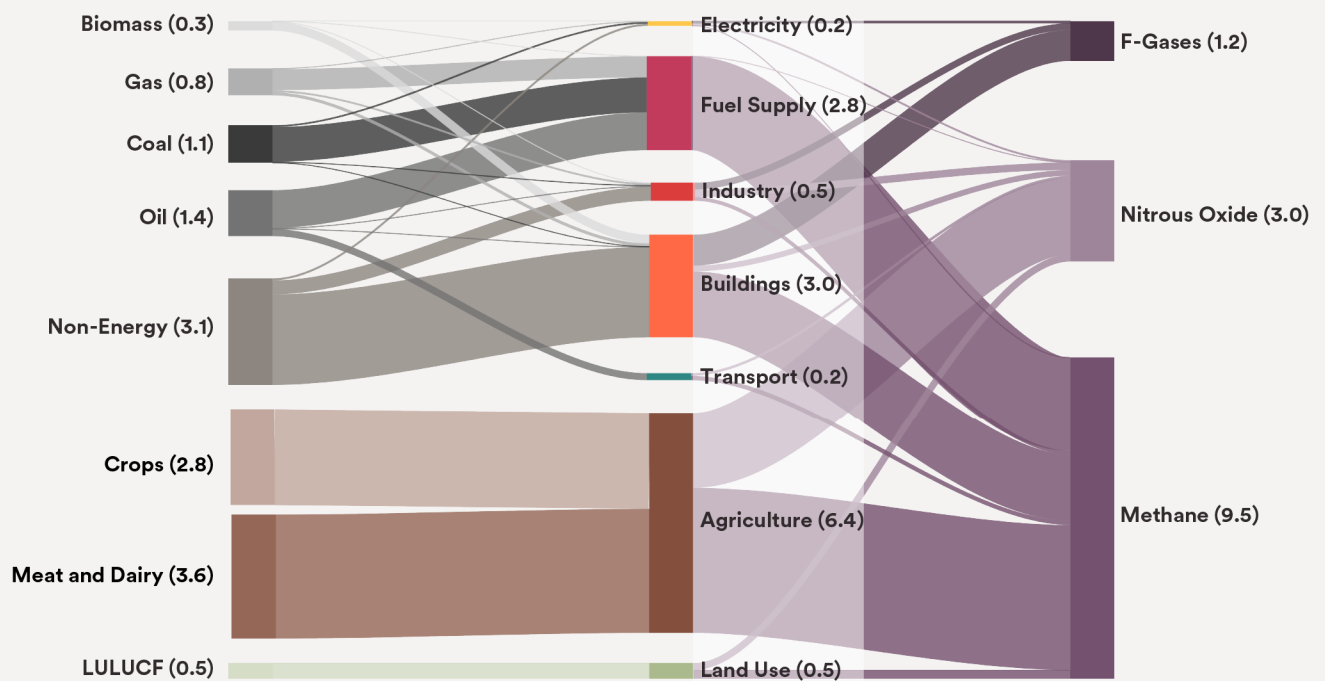
TS 6: 2015 LAND USE AND 2020 NON-CO₂ EMISSIONS FLOW

Land use (3.8 GtCO₂e, 6% of emissions in 2015)*



*For land use, we use 2015 numbers rather than 2020 numbers. Due to the complexity and uncertainty of this sector, we use historical data to provide a more accurate and detailed approximation for this sector.

Non-CO₂ (13.6 GtCO₂e, 24% of emissions in 2020)



Geographies

As mentioned, in this report we aggregated data into 10 key geographic regions: Africa; Brazil; China; Europe; India; the Rest of Latin America; the Middle East, Central Asia, and Russia; the Rest of Asia and Oceania; Southeast Asia; and the United States and Canada. The GCAM model includes 32 geographic designations, some made up of many countries. Table TS6 indicates the respective taxonomies used in this report. With 32 regions in the core model and more subregional data available in key geographies like the United States and China, data use can be flexible. Aggregating and disaggregating along geographic boundaries allows ClimateWorks Global Intelligence to align data from multiple sources and for multiple types of assessments.

TABLE TS6: GEOGRAPHY REPRESENTATION AND AGGREGATION

CWF Region	GCAM Region	Countries
Africa	Africa_Eastern	Burundi, Comoros, Djibouti, Eritrea, Ethiopia, Kenya, Madagascar, Mauritius, Reunion, Rwanda, Sudan, Somalia, Uganda
Africa	Africa_Northern	Algeria, Egypt, Western Sahara, Libya, Morocco, Tunisia
Africa	Africa_Southern	Angola, Botswana, Lesotho, Mozambique, Malawi, Namibia, Swaziland, Tanzania, Zambia, Zimbabwe
Africa	Africa_Western	Benin, Burkina Faso, Central African Republic, Cote d'Ivoire, Cameroon, Democratic Republic of the Congo, Congo, Cape Verde, Gabon, Ghana, Guinea, Gambia, Guinea-Bissau, Equatorial Guinea, Liberia, Mali, Mauritania, Niger, Nigeria, Senegal, Sierra Leone, Sao Tome and Principe, Chad, Togo
Africa	South Africa	South Africa
Asia (RO) and Oceania	Australia_NZ	Australia, New Zealand
Asia (RO) and Oceania	Japan	Japan
Asia (RO) and Oceania	South Asia	Afghanistan, Bangladesh, Bhutan, Sri Lanka, Maldives, Nepal
Asia (RO) and Oceania	South Korea	South Korea
Brazil	Brazil	Brazil
China	China	China
China	Taiwan	Taiwan
Europe	EU-12	Bulgaria, Cyprus, Czech Republic, Estonia, Hungary, Lithuania, Latvia, Malta, Poland, Romania, Slovakia, Slovenia
Europe	EU-15	Andorra, Austria, Belgium, Denmark, Finland, France, Germany, Greece, Greenland, Ireland, Italy, Luxembourg, Monaco, Netherlands, Portugal, Sweden, Spain, United Kingdom
Europe	Europe_Eastern	Belarus, Moldova, Ukraine
Europe	European Free Trade Association	Iceland, Norway, Switzerland
Europe	Europe_Non_EU	Albania, Bosnia and Herzegovina, Croatia, Macedonia, Montenegro, Serbia, Turkey
India	India	India
Latin America (RO)	Argentina	Argentina
Latin America (RO)	Central America and the Caribbean	Aruba, Anguilla, Netherlands Antilles, Antigua & Barbuda, Bahamas, Belize, Bermuda, Barbados, Costa Rica, Cuba, Cayman Islands, Dominica, Dominican Republic, Guadeloupe, Grenada, Guatemala, Honduras, Haiti, Jamaica, Saint Kitts and Nevis, Saint Lucia, Montserrat, Martinique, Nicaragua, Panama, El Salvador, Trinidad and Tobago, Saint Vincent and the Grenadines
Latin America (RO)	Colombia	Colombia
Latin America (RO)	Mexico	Mexico
Latin America (RO)	South America_Northern	French Guiana, Guyana, Suriname, Venezuela

Latin America (RO)	South America_Southern	Bolivia, Chile, Ecuador, Peru, Paraguay, Uruguay
Middle East, Central Asia, and Russia	Central Asia	Armenia, Azerbaijan, Georgia, Kazakhstan, Kyrgyzstan, Mongolia, Tajikistan, Turkmenistan, Uzbekistan
Middle East, Central Asia, and Russia	Middle East	United Arab Emirates, Bahrain, Iran, Iraq, Israel, Jordan, Kuwait, Lebanon, Oman, Palestine, Qatar, Saudi Arabia, Syria, Yemen
Middle East, Central Asia, and Russia	Pakistan	Pakistan
Middle East, Central Asia, and Russia	Russia	Russia
SE Asia	Indonesia	Indonesia
SE Asia	Southeast Asia	American Samoa, Brunei Darussalam, Cocos (Keeling) Islands, Cook Islands, Christmas Island, Fiji, Federated States of Micronesia, Guam, Cambodia, Kiribati, Lao Peoples Democratic Republic, Marshall Islands, Myanmar, Northern Mariana Islands, Malaysia, Mayotte, New Caledonia, Norfolk Island, Niue, Nauru, Pacific Islands Trust Territory, Pitcairn Islands, Philippines, Palau, Papua New Guinea, Democratic Peoples Republic of Korea, French Polynesia, Singapore, Solomon Islands, Seychelles, Thailand, Tokelau, Timor Leste, Tonga, Tuvalu, Viet Nam, Vanuatu, Samoa
U.S.A and Canada	Canada	Canada
U.S.A and Canada	U.S.A.	United States

Comparisons of GCAM, AR6, IEA, and other modeling projects

In the following pages, we provide multiple dashboards that compare our results to those of other modeling projects. This exercise provides a point of comparison and can inform discourse on outcomes and future areas of research. To be exhaustive, the exercise would require significantly more detail, including a dive into subsectors and additional geographies, assessment of activity drivers, and use of calibration data. Suffice it to say that directionally, modeling projects largely agree on emissions outcomes but differ on the pace and scale of sectoral emissions reductions.

Global Change Analysis Model

In Dashboard TS Figure 7, we compare our scenarios to the default outputs from GCAM for shared socioeconomic pathways for 2°C- and 1.5° C-compatible scenarios (RCP 2.6 and 1.9, respectively). As mentioned earlier, the SSPs were our starting points for creating the CWF Central and Ensemble scenarios. The GCAM SSP scenarios include results for all five SSPs, and we highlight the results of SSP1, the pathway most like our Central scenario. While we included both the 2° C- and 1.5° C-compatible scenarios, the key differences are highlighted by a comparison of the 1.5° C scenarios, which have the same long-term temperature outcomes. Some high-level differences emerged. Power sector emissions in the GCAM-SSPs include greater utilization of CDR including use of BECCS. This is reflected in total CDR where the GCAM-SSPs utilize more than the CWF scenarios. Fuel Supply sectors play out similarly to the power sector due to higher availability of bioenergy and use of BECCS which are more highly constrained in the CWF scenarios. To compensate for the lack of available bioenergy and CDR options, the CWF scenarios deploy deeper emissions cuts across end use sectors, particularly the Buildings and Transport sectors. Finally, Land and Agricultural sectors are slightly more ambitious in the CWF scenarios.

Intergovernmental Panel on Climate Change's Sixth Assessment Report

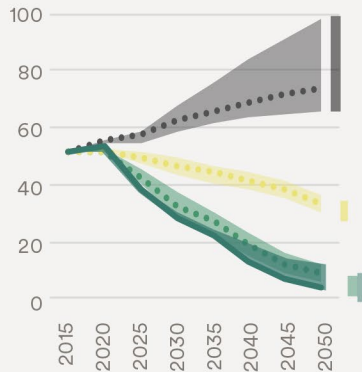
In Dashboard TS Figure 8, we compare our scenario results for the Reference and Central scenarios to results described in the recent IPCC AR6 Working Group III report on mitigation. This report gathers results from hundreds of modeling projects, including many similar RCP-class IAMs. Unfortunately, due to differences in calibration data and scope definitions of sectors, there are some difficulties in comparing the IPCC results with the CWF results. We provide outcome ranges for all scenarios within the IPCC AR6 databases for 3 types of scenarios (total of 327 scenarios): C6 scenarios (97 total), which for emissions are similar the GCAM Reference scenario; C2 scenarios (133 total), which are 1.5° C aligned with a high overshoot; and C1b scenarios (97 scenarios), which are 1.5° C aligned with a minimal overshoot. Because the ranges are so large in these scenarios, we also compared our Central scenario with the Illustrative Mitigation Pathway (IMP) Sustainable Pathway (SP) produced by the Potsdam Institute for Climate Impact Research using its REMIND model.³² Compared with the IMP SP, the Central scenario has deeper overall carbon reductions by 2050 due to larger scaling of CDR and deeper emissions reductions in the Transport sector but similar reductions in other end-use sectors. Compared with the Central scenario, the IMP SP results in a larger emissions reduction in agriculture sectors, which likely makes up for its smaller levels of emissions reductions and smaller scaling of CDR. Consequently, the IMP SP and the Central scenario reach a similar low-temperature outcome.

International Energy Agency's 2022 World Energy Outlook

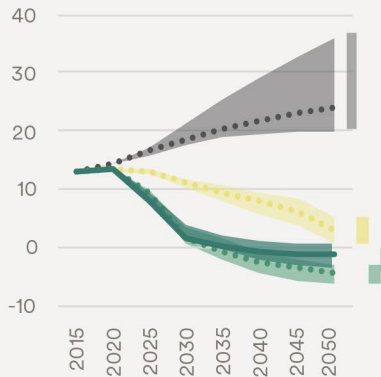
In Dashboard TS Figure 9, we compare our scenario results for the Central and Ensemble scenarios to results of the IEA's WEO scenarios (2022 SPS, APS, and NZE, and 2021 SDS). Importantly, the IEA neither covers land use sectors nor non-CO₂ emissions in any comprehensive way. There are also important scope differences in industrial and fuel supply sectors. On net, the NZE and Central scenarios are nearly identical out to 2050 for energy-related CO₂. At the sector level, however, compared with the NZE, the Central scenario has more residual emissions across end-use sectors, which are balanced with higher levels of CDR. This means the NZE scenario is most like the Zero-CCS/DAC scenarios from the Ensemble. Importantly, the NZE scenario has roughly a 50% chance of limiting warming to 1.5° C by 2100; the Central scenario results in a lower increase: 1.2° C.³³ The lower temperature outcome in the Central scenario means that scenario is far more ambitious. Use of bioenergy is another important difference in the two scenarios: the NEZ uses around 100 EJ by 2050, whereas the Central scenario uses 69 EJ.³⁴ This additional bioenergy helps explain differences in how end-use sectors reach lower emissions in the NEZ scenario without lower use of CDR. By contrast, the Central scenario is more constrained in its use of bioenergy.

TS 7: COMPARISON TO GCAM SSP RANGES (GTCO₂E/YR)

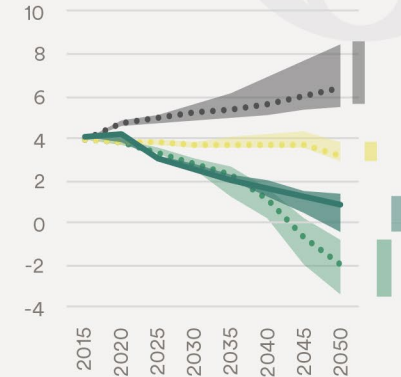
Global pathways



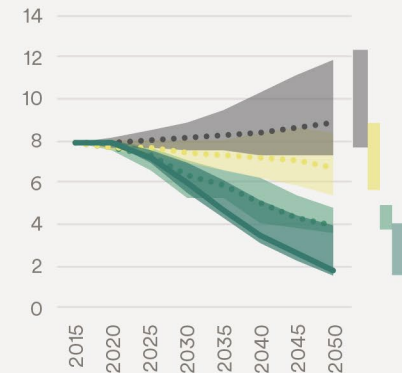
Power sector



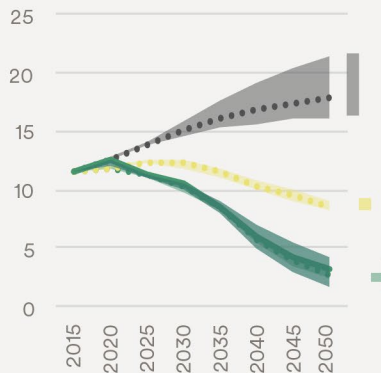
Fuel supply



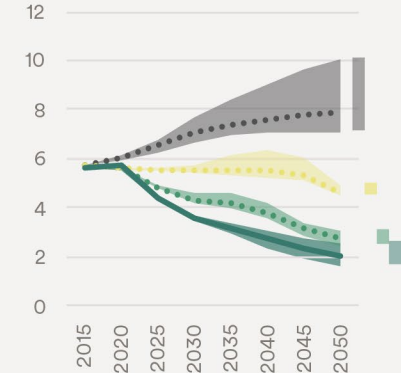
Transport sector



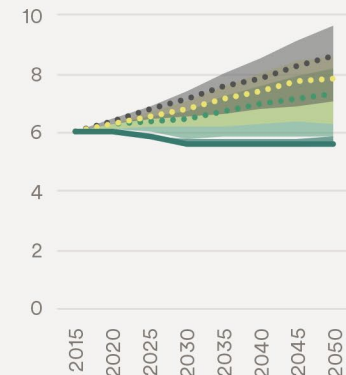
Industry sector



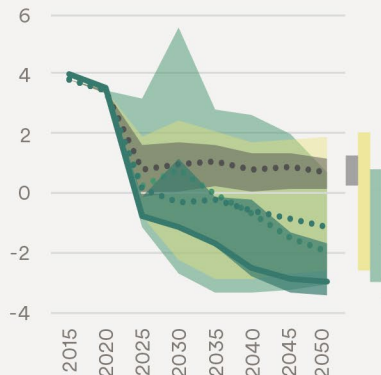
Buildings sector



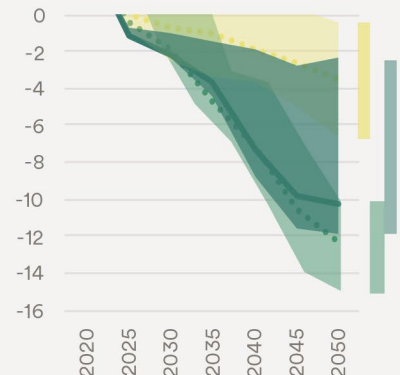
Agriculture sector



Land use sector

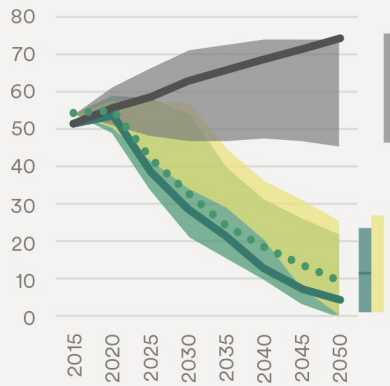


Total CDR

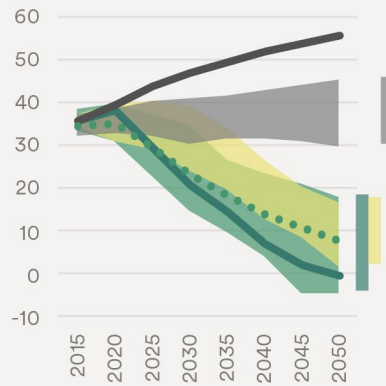


TS 8: COMPARISON TO IPCC AR6 SCENARIOS (GTCO₂E/YR)

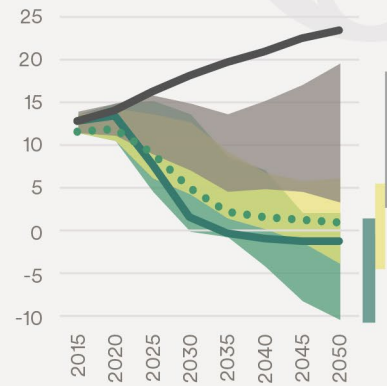
Global pathways



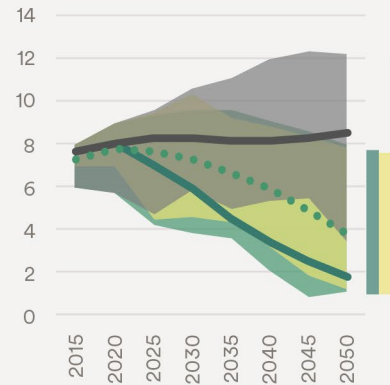
Energy CO₂ only



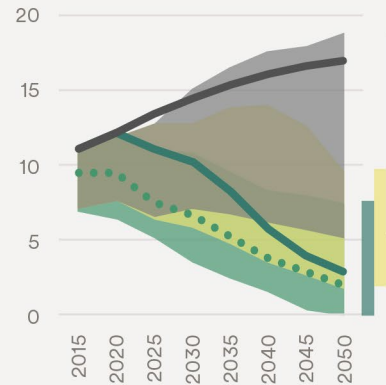
Power sector



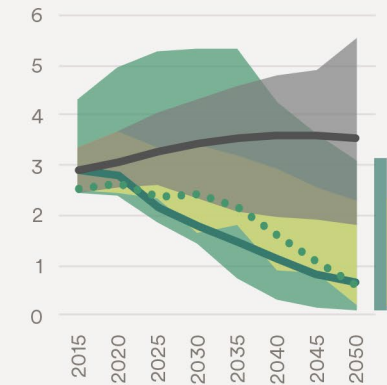
Transport sector



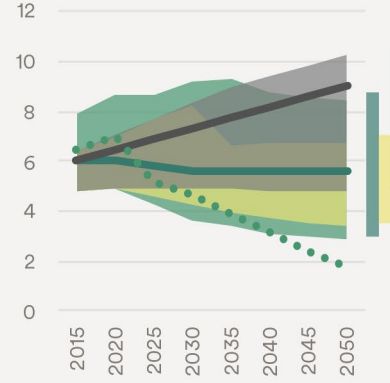
Industry sector



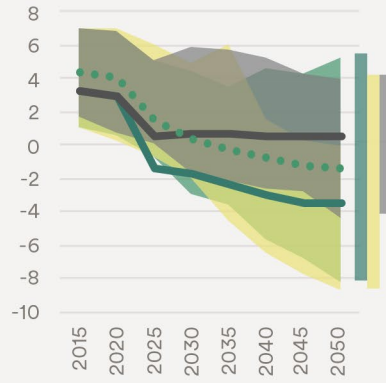
Buildings sector



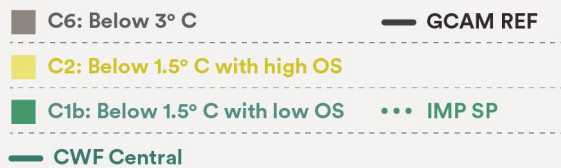
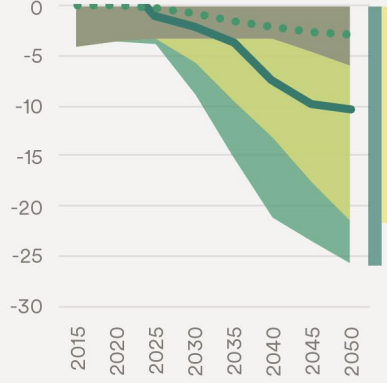
Agriculture sector



Land use sector

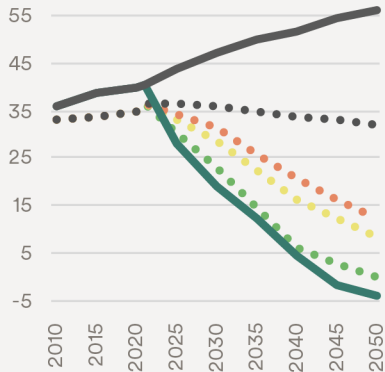


Total CDR

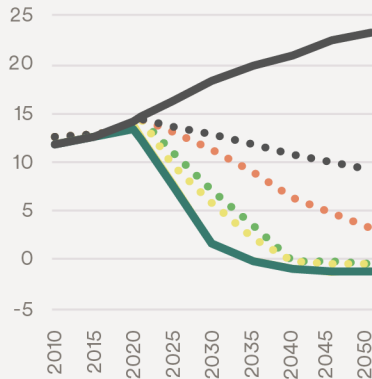


TS 9: COMPARISON TO 2022 IEA WEO (GTCO₂/YR)

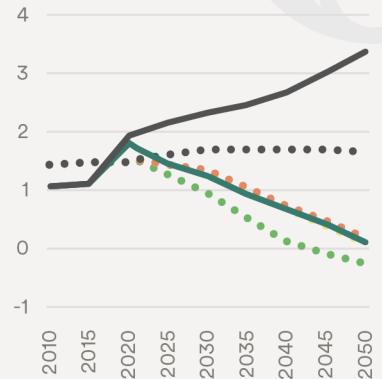
Global pathways



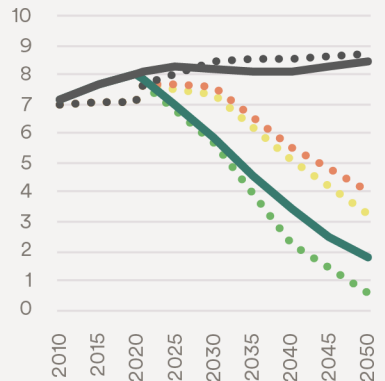
Power sector



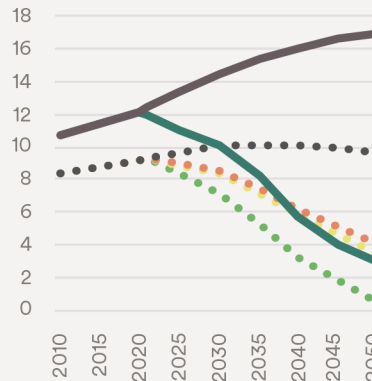
Fuel supply



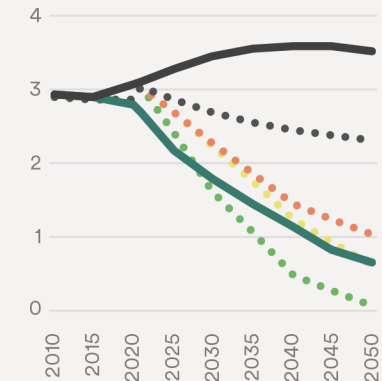
Transport sector



Industry sector



Buildings sector



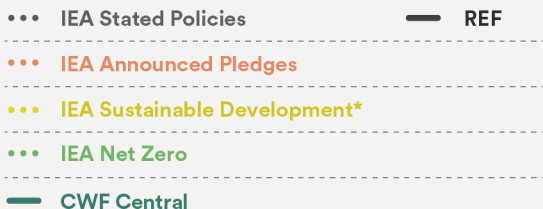
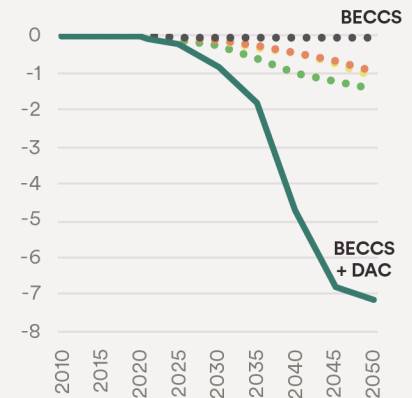
Agriculture sector

Not available:
IEA does not model
Agriculture

Land use sector

Not available:
IEA does not model
Land Use

Total tech CDR

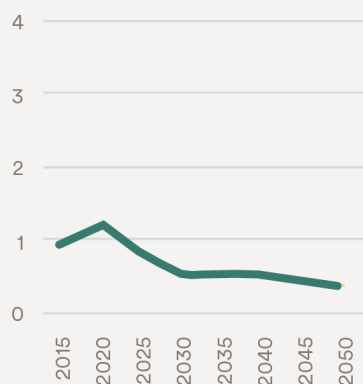


*IEA scenarios published in 2022 except for the Sustainable Development Scenario, which hasn't been updated from 2021.

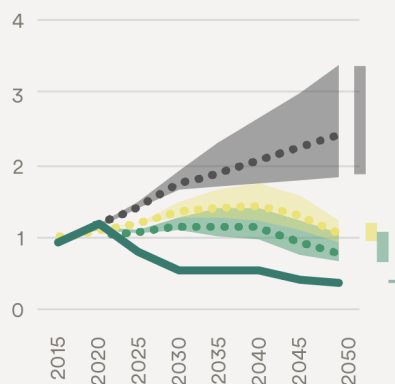
Other comparisons: Superpollutants

TS 10: SUPER-POLLUTANT GASES COMPARISON TO GCAM SSP RANGES AND IPCC AR6 SCENARIOS (GTCO₂E/YR)

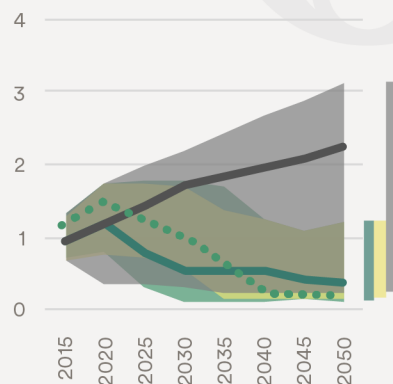
F-gases CWF ensemble



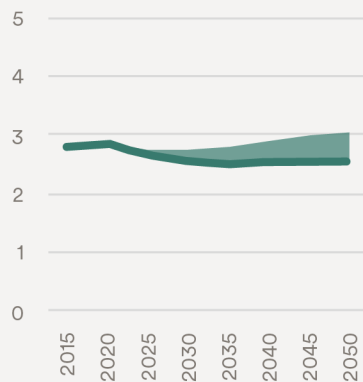
F-gases GCAM-SSP Range



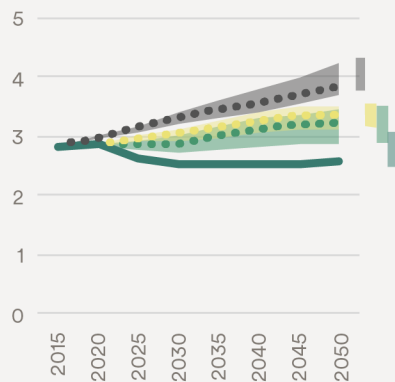
F-gases AR6 Scenarios



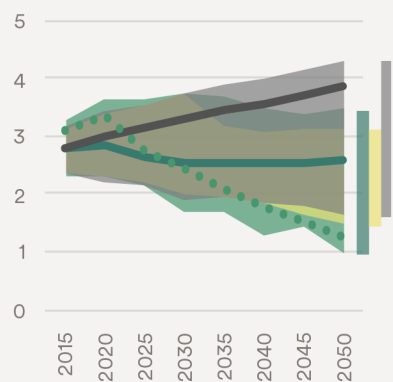
N₂O CWF ensemble



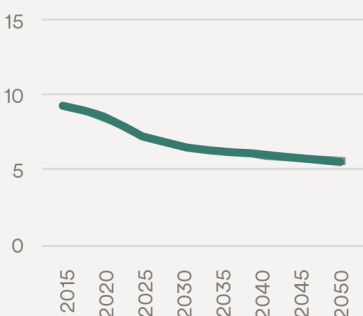
N₂O GCAM-SSP range



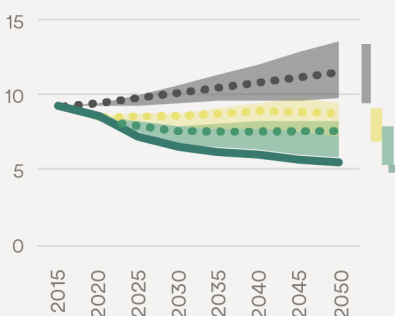
N₂O AR6 scenarios



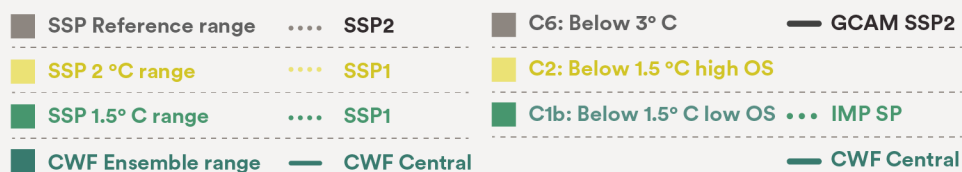
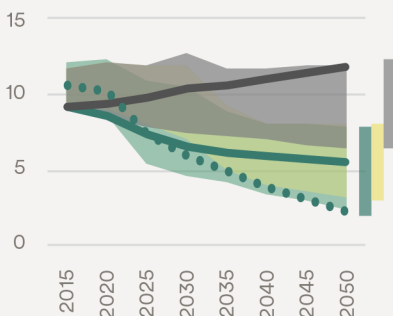
CH₄ CWF ensemble



CH₄ GCAM-SSP range



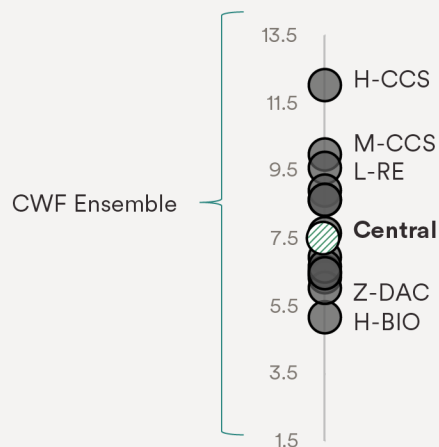
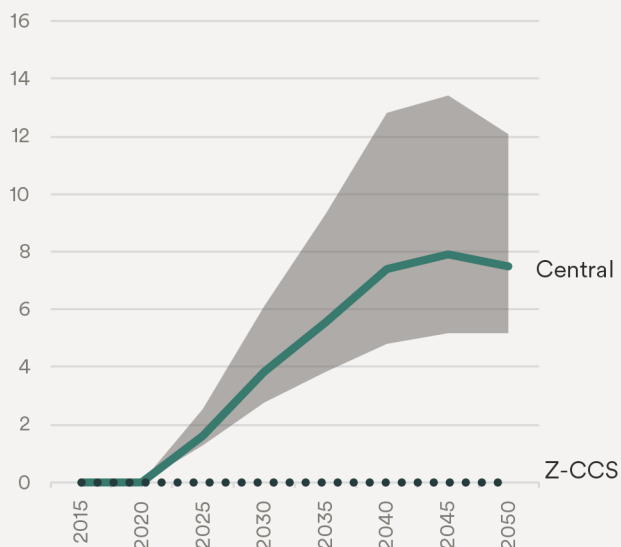
CH₄ AR6 scenarios



Other comparison figures: CCS

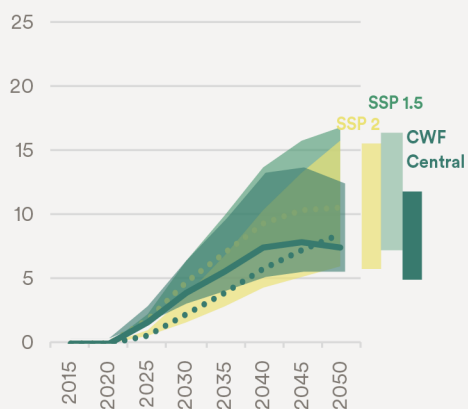
TS 11: CCS SECTOR

2020-2050 CCS range across ensemble (GtCO₂e/yr)



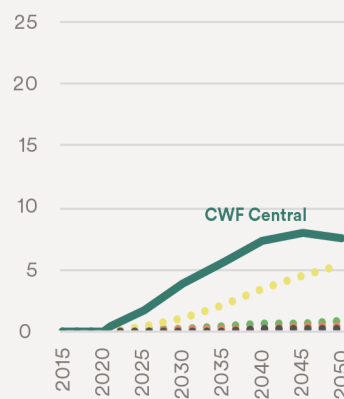
Generation by source (1000 TWh)

CWF comparison to SSP 2C and 1.5 C (GtCO₂e/yr)



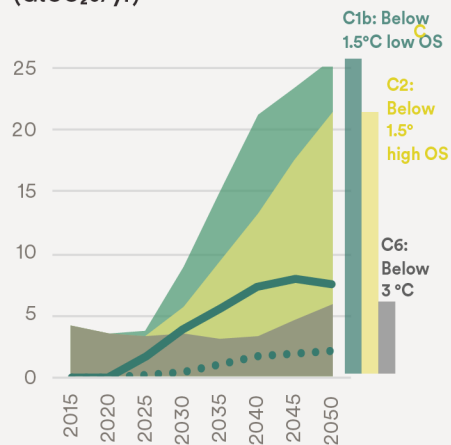
See TS 9 for legend on SSP scenarios.

CWF comparison to the IEA 2022 World Energy Outlook (GtCO₂e/yr)

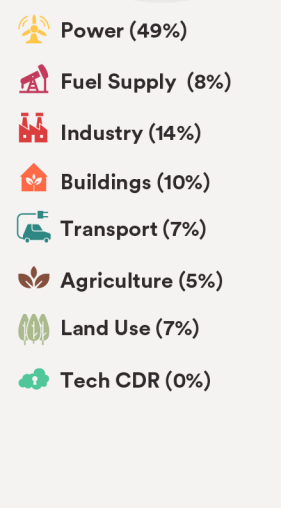


See TS 10 for legend on IEA scenarios.

CWF comparison to IPCC AR6 WGIII (GtCO₂e/yr)



See TS 8 for legend on IPCC AR6 scenarios.



		Global	Africa	Asia (RO) and Oceania	Brazil	C Asia, M East, Russia	China	Europe	India	Latin America (RO)	SE Asia	U.S. & Canada
	Electricity	16.9	0.6	1.0	0.1	1.2	6.1	1.5	2.9	0.4	0.9	2.0
	Fuel Supply	2.7	0.2	0.1	0.0	0.6	0.9	0.3	0.1	0.1	0.2	0.3
	Industry	4.7	0.2	0.2	0.0	0.5	1.7	0.3	1.2	0.1	0.3	0.3
	Buildings	3.5	0.2	0.2	0.1	0.6	0.9	0.5	0.2	0.2	0.3	0.3
	Transport	2.4	0.2	0.2	0.1	0.3	0.4	0.3	0.2	0.1	0.2	0.5
	Agriculture	1.7	0.3	0.1	0.1	0.1	0.4	0.1	0.2	0.1	0.1	0.2
	Land Use	2.4	0.7	0.0	0.4	0.3	0.1	0.1	0.1	0.2	0.2	0.3
	Tech CDR	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
TOTAL		34.2	2.4	1.8	0.8	3.6	10.5	3.2	4.8	1.3	2.2	3.8

Future research

As mentioned above, we treat this study as a living exercise. Discussions with philanthropic partners and with the scientific community allow us to set a research agenda that we carry forward. Current topics of interest include the following:

- **Expanded representation of CDR options and the latest in scientific understanding of their potential contributions:** These options include DAC technologies, ocean alkalinity enhancement, direct ocean capture, and enhanced weathering as well as the use of biochar and engineered wood and the conversion of CO₂ to durable carbon for use in consumer products and fuels. Results from recent analyses can be found in our recent publication in Nature Climate Change, Diverse carbon dioxide removal approaches could reduce impacts on the energy-water-land system.³⁵ While this current ensemble has limited CDR representation, we will update future scenarios to include this wider portfolio of options and test outcomes through new constraint scenarios.
- **Greater inclusion of alternative fuels like green hydrogen and other low-emissions synthetic fuels:** Such fuels appear promising for addressing some of the larger residual emissions in industrial and transportation sectors (i.e., in some high-heat industrial applications, for use as a feedstock, and as fuels for aviation and shipping). Reducing such residuals could decrease the need for CDR.
- **Examination of the role of lifestyle changes, including the role of shifts in energy consumption, transport, and diet, in a low-medium-high emissions outcome framework:** In the current Central scenario, we categorize these lifestyle changes as moderate, but in future studies we intend to test lower and higher levels of lifestyle changes. This would include representation of more ambitious protein transitions that emphasizing plant-based protein sources over animals, shifting away from private modes of transport, and energy consumption in buildings that better represent recent trends like remote work.
- **Connecting human impact to science to help ensure sustainable outcomes:** As mentioned throughout the report, there is a need for additional research that ensures climate change mitigation efforts center people and communities. While this report provides a high-level overview of global pathways, further applications of these scenarios must consider varied policy objectives at the local level. Future research that focuses on specific sectors and geographies will help provide additional nuance for better informed and people-focused policy recommendations.



View of Dien Khanh town in sunrise, Khanh Hoa province, central Vietnam. (iStock)

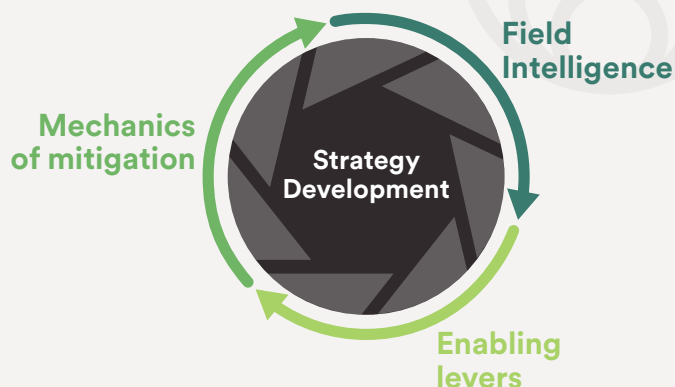
Using the ClimateWorks Ensemble

At ClimateWorks, we use the scenarios highlighted in this report to help inform the organization's portfolio strategy development process as well as our engagements with partnering philanthropies and climate advocacy organizations.

There are many frameworks that philanthropy can use to define a theory of change (TOC) or strategy. In their most basic form, TOCs include three components: (1) a theory of the *thing* you're trying to change, (2) a theory of how that *thing* might change, and (3) a theory of how you or your organization might enable that change. At ClimateWorks, we have developed one such conceptual framework for creating a climate strategy tailored to these components. This framework includes the mechanics of mitigation, field intelligence, and enabling levers (see Figure TS 13). The mechanics of mitigation refer to the economic, technological, and sometimes behavioral aspects that inform a pathway for achieving long-term climate goals as illuminated through research outlined in this report. Field intelligence refers to unique data and insights that ClimateWorks collects from climate philanthropy and grantees. We round off the process of creating a climate strategy with an examination of the enabling levers, the tools used by philanthropy and other actors to develop and implement emissions reduction strategies (see table Figure TS 10 on Understanding philanthropic levers below). These three key elements are vital to any climate philanthropy strategy, and the data and insights within this report are meant as an input to its development.

ClimateWorks provides advisory services to a wide range of philanthropic and advocacy partners. Some partners are brand new to the climate space and are looking for an overview of the science, whereas others have decades of experience and might have narrow sets of questions about individual geographies or sets of interventions for a particular sector or geography. Although we cannot answer every question, we can answer many with our integrated assessment model (GCAM). Engagement with relevant groups and communities helps formulate a research agenda for future projects, and the Ensemble of scenarios in this report are a direct result of a series of what-if questions from partners. Such engagements are ongoing, and we expect to update our scenarios every couple of years to reflect the latest science and understanding of climate mitigation. We encourage interested organizations to reach out to learn more about this process and how they might participate.

TS 13: CONCEPTUAL FRAMEWORK FOR CREATING A CLIMATE STRATEGY



Creating strategies that deliver on the climate change mitigation opportunities in this report requires transitioning from an expansive view toward increasing detail on the mechanics of mitigation, intelligence from the field seeking to enact these transitions, and the levers that enable them.

Understanding philanthropic levers

Throughout this report we describe levers as tools used by philanthropy and other climate actors when developing strategies to implement emission reduction measures. While the goal is a transition toward lower emissions, these levers are indirect as they attempt to set in motion the enabling conditions for implementation of climate policies at multiple levels of government and society at large. Programmatic strategies utilize these levers to differing degrees and many deploy these simultaneously.

TABLE TS10: LEVERS FOR CLIMATE PHILANTHROPY TO CONSIDER IN STRATEGY DEPLOYMENT

	Advocacy	Strong government policies are indispensable in order to enact large-scale, transformative climate change mitigation. By directly engaging with policymakers to advocate for smart and effective climate policies, the climate community can play a key role in the policy process and ultimately drive outsized impact.
	Communications	Through strategic communications, the climate community can drive engagement with a wide public audience, build awareness about the seriousness and urgency of the climate crisis, and convey what is needed to stop it. By boosting public engagement on climate-relevant topics, climate actors can indirectly encourage politicians and policymakers to enact ambitious climate policies.
	Diplomacy & Governance	The years-long process of negotiating the Paris Agreement demonstrates the difficulty and importance of international climate diplomacy. By illuminating the best opportunities, advocating for smart policies, and assisting with institutional capacity-building, supporting bilateral and multilateral engagements, climate actors can help countries boost the ambition of their climate targets or assist in the design of regulations to reduce the emissions stemming from transnational or international activities.
	Field-Building	To enable effective climate action, a multitude of actors (individuals, academics, investors, businesses, government) in various capacities can take on the big challenges of implementing climate solutions. For this to work well, we need a robust civil society including a thriving non-profit sector, grassroots champions, academia, informed business leadership and opportunities for engagement between these various actors. Philanthropic support for field building and engagement across these categories can help overcome barriers, identify opportunities and build the political will needed to enable climate action.
	Finance & Markets	Climate actors can help the investment community and markets better understand the financial advantages of backing climate solutions, as well as the risk of stranded assets that lose their value due to the global transition toward a net-zero emissions future. They can also encourage investors to put their money behind positive examples and divest from climate change exacerbators.
	Innovation	Innovation and risk-taking are needed to develop and deploy the technologies required to stabilize the climate. The climate community can help commission cutting-edge research, conduct demonstration projects, and assist early deployment, helping innovators turn ideas into marketable products.
	Litigation	Without adequate enforcement mechanisms, even the smartest climate policies cannot function as intended. Climate actors can help to ensure accountability by initiating or supporting legal actions that uphold climate-relevant regulations like power plant emissions standards, building codes, indigenous people's land rights, and much more.

Other resources

There are a variety of studies from various organizations that identify pathways to meet near-term and long-term temperature goals. Some are described below and include partners we work with to help inform our own thinking and work in this field. Each offers various advantages with in-depth focus on specific aspects like energy or land use only, or primarily global assessments. And while differences in approach and the original line of inquiry can lead to a range of outcomes, they offer complementary insights for a wide range of audiences that can help us collectively.

The Intergovernmental Panel on Climate Change, a U.N. body, provides the most comprehensive scientific assessment of emissions pathways compatible with limiting warming to 1.5° C in the context of sustainable development, based on a wide range of models and scenarios (including use of GCAM). It covers energy and land-use sectors and data is available within scenario portals hosted by the International Institute for Applied Systems Analysis (see data portals at <https://data.ene.iiasa.ac.at/ar6/>) and for more on recent IPCC reports including the 2022 release of Working Group III on Mitigation see: <https://www.ipcc.ch/report/sixth-assessment-report-working-group-3/>

The Integrated Assessment Modeling Consortium, an organization of scientific research institutions that pursues scientific understanding of issues associated with integrated assessment modeling and analysis (of which GCAM is a part). This organization was created to support coordination between institutes in support of the IPCC assessments cycles and has since evolved and supports coordination across many research areas. Data portals for scenarios in support of IPCC and other reports are hosted by the consortium and their institution partners found at: <https://www.iamconsortium.org/resources/databases/>

The International Energy Agency (IEA) produces the annual reports including the World Energy Outlook, which covers all energy sectors and major world regions. Data is available for a few scenarios out to 2050 and can be found at <https://www.iea.org/reports/world-energy-outlook-2022>

The U.N. Emissions Gap Report provides an annual outlook on emissions pathways, current policy progress, and pathways to achieve well below 2°C of warming, based on a synthesis of published work. Solutions to bridge the emissions gap are presented with a focus on different areas each year. For 2022 reporting see: <https://www.unep.org/resources/emissions-gap-report-2022>

Climate Action Tracker provides independent scientific analysis on progress toward limiting global warming to well below 2°C at the global and regional levels, and policy or best practice options to reduce emissions in many different geographies and sectors. <https://climateactiontracker.org/global/temperatures/>

The World Resources Institute (WRI) Data Platforms hosts a range of data platforms across topics on climate change. These cover energy and land sectors as well as tracking of pledges. More can be found at <https://www.wri.org/data/data-platforms>

The Network for Greening the Financial System (NGFS) provides guidelines and scenarios for use by central banks and supervisors that are also used within the larger financial sector for stress testing and analysis. This includes annually updated scenarios that utilize both integrated assessment models (including GCAM) and macro models. They also provide data on physical risks. Data portals and discussion can be found at <https://www.ngfs.net/ngfs-scenarios-portal/data-resources/>

Acknowledgments

This report greatly benefited from and was guided by feedback and recommendations from scientists at the Joint Global Change Research Institute (JGCRI), the University of Maryland (UMD), partnering institutes at the Integrated Assessment Modeling Consortium, and colleagues at the ClimateWorks Foundation. Special thanks to Haewon McJeon, who led policy analysis and modeling from JGCRI with support from Jay Furman and Simone Speizer (both from JGCRI), and Mel George (PhD candidate at UMD). We also appreciate many useful discussions with Jae Edmonds and Sha Yu from JGCRI, Vassilis Daioglou from Utrecht University, Elmar Kriegler and Christoph Bertram from Potsdam Institute for Climate Impact Research, and Leon Clarke and Kelly Levin from the Bezos Earth Fund. We also gratefully acknowledge the many colleagues at ClimateWorks who provided input as we created our scenarios, and those who provided advice and feedback to strengthen this report: Surabi Menon, Dan Plechaty, Makeeba Browne, Elin Matsumae, Avery Cohn, Anthony Eggert, Jan Mazurek, and Helen Mountford. Finally, we thank the program teams at the Climate and Land Use Alliance and at ClimateWorks.

Endnotes

- 1 See Joint Research Center, "Global CO₂ emissions rebound in 2021 after temporary reduction during COVID lockdown." October 2022. https://joint-research-centre.ec.europa.eu/jrc-news/global-co2-emissions-rebound-2021-after-temporary-reduction-during-covid19-lockdown-2022-10-14_en. October 2022. For emissions data see: EDGAR – Emissions Database for Global Atmospheric Research EDGAR v.7.0 accessible at https://edgar.jrc.ec.europa.eu/dataset_ghg70 Last access December 2022.
- 2 Temple, James. "We Need to Halve Emissions by 2030. They Rose Again in 2019." *MIT Technology Review*, 2019, <https://www.technologyreview.com/2019/12/04/131747/we-need-to-halve-emissions-by-2030-they-rose-again-i-in-2019/>.
- 3 Ou, Yang et al. "Can Updated Climate Pledges Limit Warming Well Below 2°C?" *Science* 374, no. 6568 (2021), <https://www.science.org/doi/10.1126/science.abl8976>.
- 4 For a synthesis of the Shared Socioeconomic Pathway narratives, quantitative elements, and integrated assessment model scenarios of energy, land use, and emissions, see Riahi, K. et al. "The Shared Socioeconomic Pathways and Their Energy, Land Use, and Greenhouse Gas Emissions Implications: An Overview." *Global Environmental Change* 42 (2017): 153-68, <https://doi.org/10.1016/j.gloenvcha.2016.05.009>
- 5 For more on Shared Socioeconomic Pathway extensions, see O'Neill, B. C. et al. "Achievements and Needs for the Climate Change Scenario Framework." *Nature Climate Change* 10 (2020): 1074-84, <https://doi.org/10.1038/s41558-020-00952-0>.
- 6 Olivier J.G.J. (2022), Trends in global CO₂ and total greenhouse gas emissions: 2021 Summary report. Report no. 4758. PBL Netherlands Environmental Assessment Agency, The Hague. <https://www.pbl.nl/en/publications/trends-in-global-co2-and-total-greenhouse-gas-emissions-2021-summary-report>
- 7 *Ibid.*
- 8 GCAM is coupled with a simplified climate model known as Hector to look at temperature impacts. Hector indicates that the GCAM-CWF scenario has a limited overshoot in temperature (overshoot is a temporary rise in temperature above a targeted temperature at any time between now and 2100), with a 50% probability of meeting 1.35° C and therefore a higher probability of meeting 1.5° C by 2100. We also ran the scenario through the simplified climate model MAGICC, which indicated a slight overshoot of around 10% over 1.5° C. This suggests that despite the potential for a small overshoot, the scenario is still compatible with the Paris Agreement and like a C1 category scenario as seen in the IPCC Working Group 3 mitigation report. IPCC, 2022: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley, (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA. doi: 10.1017/9781009157926, <https://www.ipcc.ch/report/sixth-assessment-report-working-group-3/>.
- 9 Calvin, K. et al. GCAM v5.1: representing the linkages between energy, water, land, climate, and economic systems. *Geosci. Model Dev.* 12, 677–698 (2019), doi:10.5194/gmd-12-677-2019
- 10 IPCC, "Synthesis report of the IPCC Sixth Assessment Report." 2023. https://report.ipcc.ch/ar6syr/pdf/IPCC_AR6_SYR_SPM.pdf
- 11 For more on global warming potentials see: Global Warming Potential Values – GHGprotocol.org: https://www.ghgprotocol.org/sites/default/files/ghgp/Global-Warming-Potential-Values%20%28Feb%2016%202016%29_1.pdf. Last accessed December 2022.
- 12 Other assessments differ on this figure, as it depends on scope. For instance, refining emissions are sometimes included in industrial emissions, and the same can be said for emissions associated with upstream mining and fuel extraction.
- 13 https://climateanalytics.org/media/temperature-overshoots_ar6.pdf
- 14 For more on leakage and a discussion on the nitrogen cycle, see Wolfram, P. et al. "Using Ammonia as a Shipping Fuel Could Disturb the Nitrogen Cycle," *Nature Energy* 7 (2022): 1112-14, <https://www.nature.com/articles/s41560-022-01124-4>.
- 15 Crippa, M., Solazzo, E., Guizzardi, D. et al. Food systems are responsible for a third of global anthropogenic GHG emissions. *Nat Food* 2, 198–209 (2021). <https://doi.org/10.1038/s43016-021-00225-9>
- 16 In our 2020 report, we saw a reduction from the Reference case of around 8 GtCO₂e. In this round, we see a reduction of about 3.4 Gt. This reduction is due to a modeling update in GCAM that limited our ability to model changes in this sector. We aim to correct for this in later modeling.
- 17 Pastureland for meadows used for feed rises so that net total pastureland grows — but importantly, there is a net negative emissions benefit.
- 18 Land-use-related estimates are highly uncertain. For 2020 we applied a correction factor by calculating the difference between GCAM results and those from the Food and Agriculture Organization (FAO), which provides annual estimates of total land-use-related emissions. This allows a better match between our reported data and other sources. For other historical values we use GCAM statistics directly, as they better approximate other sources. No changes were made for values other than the 2020 value. For more on FAO statistics, see FAOSTAT (2022), Statistics Division of the Food and Agricultural Organisation of the UN: www.fao.org/faostat, Last access December 2022.
- 19 IPCC, 2022: Summary for Policymakers. In: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley, (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA. doi: 10.1017/9781009157926.001
- 20 This refers to metrics that normalize emissions data into carbon dioxide equivalents.
- 21 See Calvin, K. et al. GCAM v5.1
- 22 *Ibid.*
- 23 Riahi, K. et al. "The Shared Socioeconomic Pathways and Their Energy, Land Use, and Greenhouse Gas Emissions Implications: An Overview." *Global Environmental Change* 42 (2017): 153-68, <https://doi.org/10.1016/j.gloenvcha.2016.05.009>. And Calvin, K. et al. GCAM v5.1
- 24 See Climate Action Tracker (2022). The CAT Thermometer. November 2022. Available at: <https://climateactiontracker.org/global/cat-thermometer/> Last accessed December 2022.
- 25 See table II.3 on page 119 in IPCC, 2022: Annex III: Scenarios and modelling methods [Guivarch, C., E. Kriegler, J. Portugal-Pereira, V. Bosetti, J. Edmonds, M. Fisschedick, P. Havlik, P. Jaramillo, V. Krey, F. Lecoq, A. Lucena, M. Meinshausen, S. Mirasgedis, B. O'Neill, G.P. Peters, J. Rogelj, S. Rose, Y. Saheb, G. Strbac, A. Hammer Strømman, D.P. van Vuuren, N. Zhou (eds.)]. In IPCC, 2022: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley, (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA. doi: 10.1017/9781009157926.022, https://report.ipcc.ch/ar6wg3/pdf/IPCC_AR6_WGIII_Annex-III.pdf
- 26 For more see: Ou et al., "Can Updated Climate Pledges Limit Warming?"
- 27 O'Neill, Brian C., et al. "The Roads Ahead: Narratives for Shared Socioeconomic Pathways Describing World Futures in the 21st Century." *Global Environmental Change* 42 (2017): 169-80, doi:10.1016/j.gloenvcha.2015.01.004; Riahi et al., "Shared Socioeconomic Pathways; and Van Vuuren, Detlef P. et al. "A New Scenario Framework for Climate Change Research: Scenario Matrix Architecture." *Climatic Change*, 122, no. 3 (2014): 373-86, <https://link.springer.com/article/10.1007/s10584-013-0906-1>.
- 28 Rogelj, Joeri et al. "Mitigation Pathways Compatible With 1.5° C in the Context of Sustainable Development." Chapter 2 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, Masson-Delmotte, V. et al., eds., IPCC, 2018, https://www.ipcc.ch/site/assets/uploads/sites/2/2019/02/SR15_Chapter2_Low_Res.pdf.
- 29 For more discussion on the RCP-SSP Framework and mention of extensions, see O'Neill, et al. "Achievements and Needs."
- 30 Van Vuuren, Detlef P. et al. "Alternative Pathways to the 1.5° C Target Reduce the Need for Negative Emission Technologies." *Nature Climate Change* 8, no. 5 (2018): 391-7, <https://ideas.repec.org/a/nat/natclci/v8y2018i5d10.1038/s41558-018-0119-8.html>.
- 31 Grubler, Arnulf et al. "A Low Energy Demand Scenario for Meeting the 1.5° C Target and Sustainable Development Goals Without Negative Emission Technologies." *Nature Energy* 3, no. 6 (2018): 517-25, <https://www.nature.com/articles/s41560-018-0172-6>.
- 32 For more on the REMIND sustainable development scenario, see Soergel, Bjoern et al. "A Sustainable Development Pathway for Climate Action Within the UN 2030 Agenda." *Nature Climate Change* 11, no. 8 (2021): 656-64, <https://www.nature.com/articles/s41558-021-01098-3>. Also see Luderer, Gunnar et al. "Impact of Declining Renewable Energy Costs on Electrification in Low-Emission Scenarios." *Nature Energy* 7, no. 1 (2022): 32–42, <https://www.nature.com/articles/s41560-021-00937-z>.
- 33 The Net Zero Emissions by 2050 Scenario (NZE) has a 50% probability of limiting temperature rise 1.5° C which is a lower probability threshold than that of the CWF Central scenario. See IEA (2022), Global Energy and Climate Model, IEA, Paris <https://www.iea.org/reports/global-energy-and-climate-model>, License: CC BY 4.0.
- 34 For more on the IEA's NZE and use of bioenergy see: IEA. "What does net-zero emissions by 2050 mean for bioenergy and land use? -Analysis." <https://www.iea.org/articles/what-does-net-zero-emissions-by-2050-mean-for-bioenergy-and-land-use>.
- 35 Fuhrman, J., Bergero, C., Weber, M. et al. Diverse carbon dioxide removal approaches could reduce impacts on the energy–water–land system. *Nat. Clim. Chang.* 13, 341–350 (2023). <https://doi.org/10.1038/s41558-023-01604-9>

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