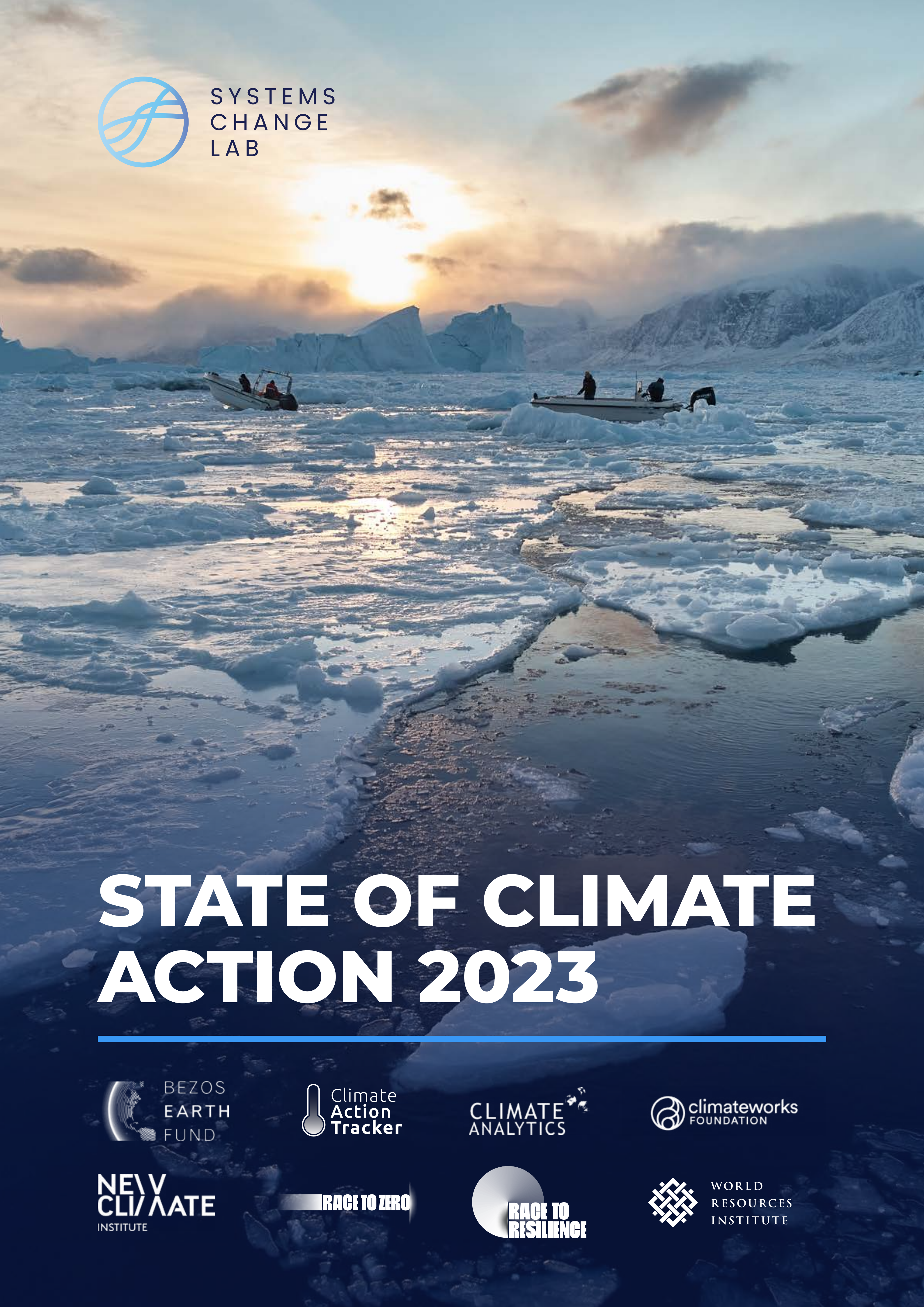

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STATE OF CLIMATE ACTION 2023

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About the Authors

Lead Authors: Sophie Boehm, Louise Jeffery, Judit Hecke, Clea Schumer, Joel Jaeger, Claire Fyson, and Kelly Levin

Chapter Authors:

- **Methodology:** Joel Jaeger, Sophie Boehm, Judit Hecke, Clea Schumer, and Louise Jeffery
- **Power:** Jason Collis, Marie-Charlotte Geffray, Clea Schumer, Joel Jaeger, and Claire Fyson
- **Buildings:** Emily Daly and Louise Jeffery
- **Industry:** Anna Nilsson, Neelam Singh, and Maeve Masterson
- **Transport:** Stephen Naimoli, Sebastian Castellanos, Judit Hecke, Michael Petroni, and Joel Jaeger
- **Forests and Land:** Sophie Boehm, Michelle Sims, and Emma Grier
- **Food and Agriculture:** Richard Waite, Raychel Santo, and Mulubrhan Balehegn
- **Technological Carbon Removal:** Katie Lebling and Claire Fyson
- **Finance:** Joe Thwaites and Anderson Lee

GHG Emissions Dataset: William Lamb

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Foreword

We face two seemingly irreconcilable truths in today's battle against climate change.

***First,* we are deep in the climate emergency.** This year's *State of Climate Action* finds that only one of the 42 indicators of sectoral climate action assessed—the share of electric vehicles in passenger car sales—is on track to meet its 2030 target. Progress falls woefully short across the board. For example, coal needs to be phased out of electricity generation seven times faster than recent rates, and the annual rate of deforestation – equivalent to 15 football fields per minute in 2022 - needs to be reduced four times faster. It's no surprise that July's global temperature was the highest monthly temperature in 120,000 years as a result. Or that wildfires, torrential rain and marine heatwaves are becoming more visible, with vulnerable communities and Global South countries disproportionately affected. Overall, the climate impacts and trends we've witnessed in 2023 have been a wake-up call—even more alarming than many climate scientists previously forecasted. And early indications are that carbon dioxide levels in 2023 will be at record levels, at the very time they should be steeply declining.

***Second,* we are seeing spectacular gains that are surprising even optimists.** Just in the last twelve months, new developments have been outstripping the expectations of experts from even a few years ago. Today, utility-scale solar photovoltaics and onshore wind are the cheapest options for electricity generation in the large majority of countries. And global renewable capacity additions are likely to increase by a third this year – the largest annual increase ever. Electric car markets are seeing exponential growth, comprising 10% of all new cars sold being in 2022, up from 1.6% in 2018. Preliminary satellite data from Brazil's national space agency indicate that deforestation fell by over 30 percent during President Lula's first six months in office. Global sales of heat pumps witnessed another year of double-digit growth, with sales in Europe growing by almost 40%. And thanks to the passage of the Inflation Reduction Act in the United States, companies are announcing hundreds of clean energy manufacturing facilities, turbocharging battery and electric vehicle production and creating tens of thousands of new jobs. These examples show that rapid change to address climate change is possible.

We must face these seemingly inconsistent truths together. Both realities explain why people can find themselves feeling radically optimistic or pessimistic. But we must embrace both: our collective failure to address climate change thus far, as well as our exponential progress in some sectors. The window to reach our climate goals is rapidly closing, but we have learned that many of the solutions we need can spread even more quickly than we previously imagined. Of course, this is only true if we fully dedicate ourselves to the challenge at hand.

This year's report seeks to answer three questions. What does the latest climate science indicate is required for each sector of the economy? How is our collective performance stacking up against these 1.5°C-aligned targets? And where are we seeing positive exponential change that we can build on?

These findings on the *State of Climate Action* come at a pivotal moment. This year, as the first Global Stocktake under the Paris Agreement culminates at COP28, world leaders must recognize the insufficient progress to date and chart a path forward that builds on the successes we're seeing. This moment should serve as a springboard for accelerated actions to mitigate climate change, including for equitably phasing out fossil fuels and scaling renewable energy, transforming food systems while halting and reversing deforestation, enhancing adaptation and responding to losses and damages, and scaling and shifting finance.

Transformational change can take off but will not happen automatically, especially in countries and communities that lack enough resources and technical capacity. Such transitions must be nurtured by leadership, smart policies and incentives, innovation, strong institutions, and changes in behavior and values. While difficult, accelerating these changes — and doing so equitably — is not impossible. And although the climate crisis continues to intensify, the future will be decided by us.

It's not too late.

H.E. Razan Al Mubarak
UN Climate Change High-Level Champion from the COP28 Presidency

Ani Dasgupta
President and CEO, World Resources Institute

Bill Hare
CEO, Climate Analytics

Niklas Höhne
NewClimate Institute

Rachel Jetel
Co-Director, Systems Change Lab, World Resources Institute

Kelly Levin
Co-Director, Systems Change Lab, Bezos Earth Fund

Mahmoud Mohieldin
UN Climate Change High-Level Champion from the COP27 Presidency

Helen Mountford
President and CEO, ClimateWorks Foundation

Andrew Steer
President and CEO, Bezos Earth Fund

Executive Summary

At the 28th Conference of the Parties (COP28), the world can jump-start an urgently needed course correction on climate change as Parties respond to findings from the first Global Stocktake. As the crux of the Paris Agreement's mechanism for ratcheting up ambition, this process offers leaders across government, civil society, and the private sector the chance not only to issue a report card on implementation of the Paris Agreement thus far, including progress made in limiting global warming to 1.5°C, but also to provide a roadmap for combatting this crisis. These same leaders can then respond decisively to the Global Stocktake's findings by making concrete commitments at COP28 that, together, serve as a powerful springboard for greater ambition and more immediate climate action. Governments, for example, can start by negotiating a decision that prioritizes critical mitigation actions this decade, such as phasing out unabated fossil fuels in electricity generation, halting deforestation and degradation, and shifting to zero-carbon transportation. A successful Stocktake should also inform the next round of nationally determined contributions (NDCs) in 2025, prompting countries to strengthen existing economy-wide and sector-specific targets for 2030, as well as set new ones for 2035 and beyond.

Failure to seize this moment and dramatically accelerate ambitious climate action across all sectors will exact a high price, with far-reaching consequences for all life on Earth. In modeled pathways that limit global temperature rise to 1.5°C with no or limited overshoot, greenhouse gas (GHG) emissions peak immediately and by 2025 at the latest, and then decline by a median of 43 percent by 2030 and 60 percent by 2035, relative to 2019. Carbon dioxide (CO_2) emissions, specifically, reach net zero by midcentury (IPCC 2022b, 2023). Yet, in practice, human-caused GHG emissions continue to rise, increasing nearly 10 percent relative to 2010 and 50 percent relative to 1990 (Minx et al. 2021; European Commission and JRC 2022). In 2019, they reached an all-time high, with the consumption patterns of the world's highest-earning households accounting for a disproportionately large share of emissions (IPCC 2022b). And with the current 1.1°C of global temperature rise, climate change is already wreaking havoc across the planet—driving temperatures to extremes, rapidly melting glaciers and ice sheets, fueling record-breaking warming in the ocean, and supercharging droughts, floods, wildfires, and cyclones. These changes have brought devastating impacts to communities around the world, often undermining hard-won development gains, and every fraction of a degree of warming will intensify these threats, particularly to the more than 3 billion people living in highly vulnerable countries. Even temporarily overshooting the Paris Agreement's 1.5°C limit, for example, will lead to much more severe, oftentimes irreversible, impacts (IPCC 2022a).

Highlights

- To support the Global Stocktake, this report translates the Paris Agreement's temperature limit into 1.5°C-aligned targets across sectors and offers a frank assessment of recent progress toward them.
- This sectoral report card shows that transformations are not occurring at the required pace and scale. Only 1 of 42 indicators assessed—the share of electric vehicles in passenger car sales—is on track to reach its 2030 target. And while change is heading in the right direction for nearly three-quarters of the indicators, the pace remains promising but insufficient for 6 and at well below the required speed for another 24. For 6, recent trends are heading in the wrong direction entirely, and data are insufficient to evaluate the remaining 5.
- But even when change is heading in the right direction, getting on track for 2030 will require an enormous acceleration in effort. Coal-fired power, for example, needs to be phased out seven times faster. Deforestation rates must decline four times faster. And increases in the ratio of investment in low-carbon to fossil fuel energy supply need to occur more than ten times faster.
- Progress made in adopting zero-carbon technologies—solar and wind power, heat pumps, and electric vehicles, for example—shows that, fortunately, rapid, nonlinear change is not only possible but already underway in some sectors. And this assessment accounts for such change.
- Nearly halfway through this decisive decade, leaders must pick up the pace and shift into emergency mode. They must nurture rapid, nonlinear growth, accelerate progress, and expand much-needed support to all sectors, especially those lagging furthest behind.

Changing course to limit warming to 1.5°C will require the world to overcome barriers that still stand in the way of transitioning to a net-zero future amid a rapidly changing geopolitical landscape. Powerful vested interests—from fossil fuel industry lobbyists to multinational agricultural corporations—still defend the emissions-intensive status quo. Investments in the research and development of more nascent zero-carbon technologies remain far too low. And many countries have yet to adopt the supportive policies needed to accelerate sectoral transformations (Boehm

et al. 2022). At the same time, Russia's invasion of Ukraine continues to challenge diplomacy, reshape geopolitics, and complicate multilateral efforts to mitigate climate change (IEA 2023p). The war has also intensified the global food crisis by disrupting agricultural production across the world's breadbasket, Ukrainian grain exports, and fertilizer trade. Subsequent rises in food prices have hit hardest those living in poverty, particularly in low- and middle-income countries (Glauber and Laborde 2023). Coupled with the burden of a costly COVID-19 recovery, this cataclysm of recent events poses significant obstacles to climate action, effectively sapping government spending and saddling many countries with record-high debt, inflation, and interest rates (Wheatley 2023).

Fortunately, these obstacles are surmountable, and recent years have witnessed significant action, particularly among major emitters. Although some countries have reopened fossil fuel plants following Russia's invasion of Ukraine, others have used this exogenous shock as a justification to increase investments in zero-carbon technologies in pursuit of energy-independent futures.[1] The European Union, for example, installed record amounts of wind and solar in 2022 and accelerated efficiency improvements and heat pump installations, all of which have contributed to rapid declines in fossil fuel demand (Ewen and Brown 2023; Zeniewski et al. 2023). China is poised to meet its renewable energy capacity targets for 2030, as much as five years early (GEM 2023c); in 2022, it spent nearly US$550 billion on zero- and low-carbon technologies—almost as much as the combined investments made by all other countries in that same year (BloombergNEF 2023b). And the United States recently passed the Inflation Reduction Act, which will provide more than $370 billion (and up to $1.2 trillion, with the range driven by uncertainty over how much tax credits will be claimed) over 10 years to projects that reduce GHG emissions and enhance carbon removal—the largest investment in climate and energy in the country's history (White House 2023; Jiang et al. 2022; Goldman Sachs 2023). Such momentum is also growing globally, with worldwide investments in low-carbon energy supply exceeding those in fossil fuels for the first time in 2022 (IEA 2023m).[2]

A growing body of evidence also shows that, with supportive policies, rapid, nonlinear change is already occurring in some sectors and regions. Over the last five years, the share of electric vehicles (EVs) in light-duty vehicle sales has grown exponentially at an average annual rate of 65 percent—up from 1.6 percent of sales in 2018 to 10 percent of sales in 2022 (IEA 2023e). In the past decade, power generation costs have declined 80 percent for solar photovoltaics (PV) and 65 percent for onshore wind (IRENA 2023b), making these technologies the cheapest sources of new-build electricity generation for at least two-thirds of the global population (BloombergNEF 2020). And the price of battery storage, a technology that enables greater adoption of many renewable power sources, also dropped by 89 percent between 2010 and 2021 (BloombergNEF 2022a). These bright spots show that, under the right conditions, change can take off. Expanding such progress to all sectors will require leaders to prioritize supportive regulations and incentives, investments in innovation and in scaling existing solutions, courageous leadership, institutional strengthening, and behavior change and shifts in social norms.

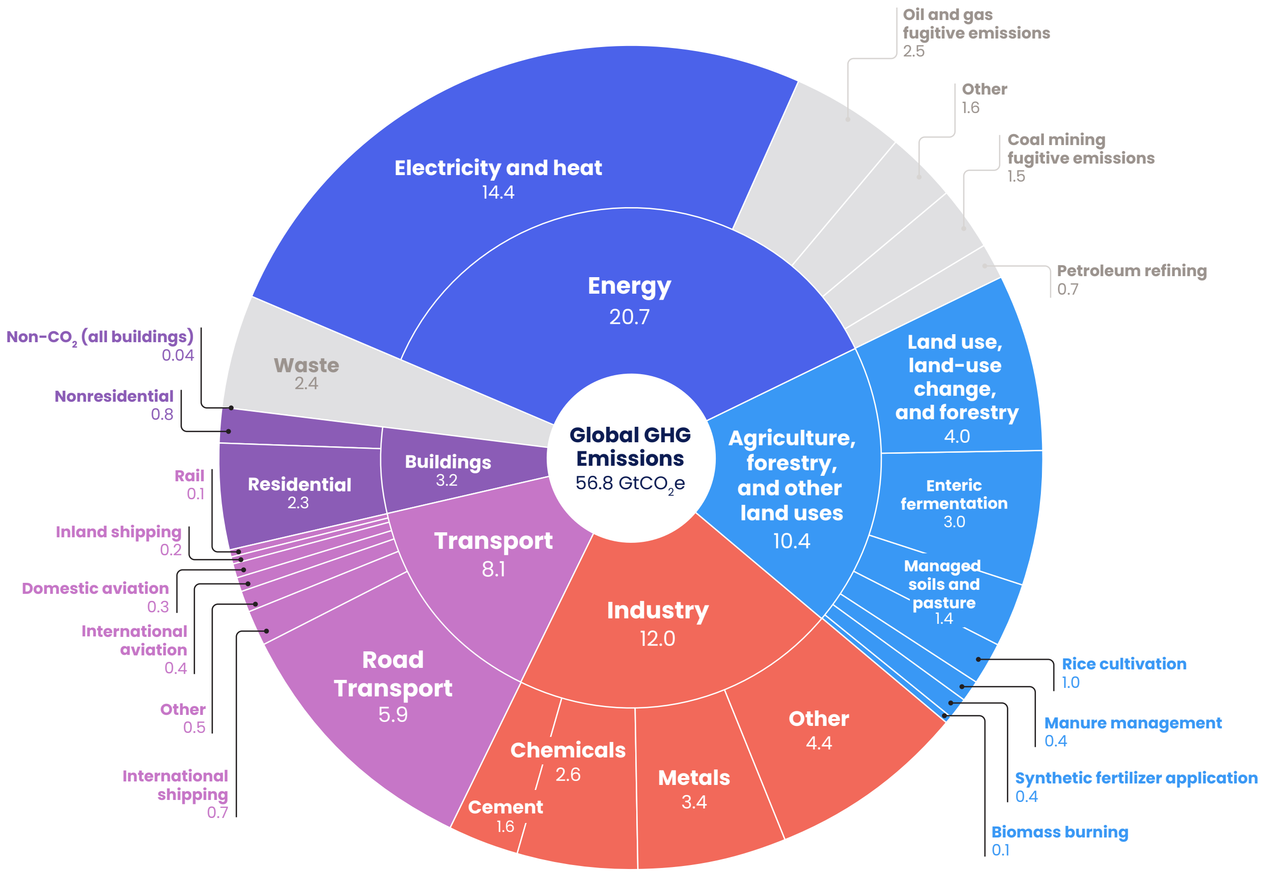
Although the window of opportunity to limit warming to 1.5°C is narrowing, achieving this Paris Agreement goal is still technically feasible—and the benefits of securing this future are enormous. Cutting GHG emissions can serve as a first line of defense by helping to reduce the frequency and severity of impacts to which vulnerable communities around the world must adapt, as well as minimizing some (though not all) losses and damages. Mitigating climate change, a direct driver of biodiversity loss, can also lower the risk of irreversible ecosystem loss and degradation. And when implemented appropriately, these same measures can generate a wide range of benefits to sustainable development, such as improved air quality, increased access to clean energy, diversified livelihoods, and enhanced food security (IPCC 2022b). When considering the alternative, these benefits of climate action cannot be overstated.

Justice and equity must take center stage in global efforts to accelerate sectoral transformations. The benefits reaped from limiting warming to 1.5°C must be shared equitably, and achieving this goal, in large part, will require that those impacted by these changes have the power to shape decision-making processes. It will also depend on the rapid scale-up of climate finance, particularly funding for developing countries. Without additional, accessible, and high-quality finance, these countries will likely struggle to implement mitigation measures and secure the benefits—both local and global—of limiting warming to 1.5°C. Yet wealthy countries' delivery on international climate finance commitments remains far behind (OECD 2022a; Songwe et al. 2022). Efforts to mitigate climate change will also create new challenges (IPCC 2022b). Retiring coal-fired power plants, for example, risks displacing workers, disrupting local economies, and reconfiguring the social fabric of communities. Reforestation efforts may also harm local livelihoods, intensify food insecurity, and undermine efforts to eliminate poverty if implemented inappropriately. And some climate policies, such as carbon taxes, can be regressive if they don't include provisions to offset increased costs for low-income communities. Fortunately, many measures exist to support a just transition and help ensure that no one is left behind as the world moves toward a future of net-zero emissions.

About this report

To support the Global Stocktake process, the *State of Climate Action* series translates the Paris Agreement's 1.5°C temperature limit into sectoral targets and provides a roadmap that leaders can follow to help close the GHG emissions gap. Building on CAT (2020a, 2020b, 2023a), Lebling et al. (2020), Boehm et al. (2021, 2022), and Climate Analytics (2023), this fourth installment features 1.5°C-aligned targets primarily for 2030 and 2050, as well as associated indicators, for power, buildings, industry, transport, forests and land, and food and agriculture that the literature suggests are among the best available to monitor sectoral climate mitiga-

FIGURE ES-1 | Global net anthropogenic GHG emissions by sector in 2021



Notes: CO_2 = carbon dioxide; GHG = greenhouse gas; $GtCO_2e$ = gigatonnes of carbon dioxide equivalent. Note that sectors in grey are excluded from this report.

Sources: Minx et al. (2021); European Commission and JRC (2022).

tion pathways. Together, these sectors accounted for roughly 85 percent of net anthropogenic GHG emissions globally in 2021 (Figure ES-1), with waste and upstream energy emissions, such as fugitive emissions from fossil fuel extraction and petroleum refining, accounting for the remaining 15 percent. Additionally, this report includes targets and indicators to track progress made in scaling up carbon removal technologies and climate finance, both of which will be needed to achieve the Paris Agreement's 1.5°C limit on global temperature rise. While a similar effort is warranted for adaptation, this report's scope is limited to mitigation, though achieving some targets would deliver considerable benefits to adaptation.

The series also provides a report card on collective efforts to mitigate climate change by evaluating recent progress made toward (or away from) 2030 targets. To assess global progress for most indicators, we used the past 5 years of historical data (or 10 years for forests and land indicators where possible) to project a linear trendline from the most recent year of data to 2030 and then compared this trendline to the rate of change needed to reach 1.5°C-aligned targets for the same year. With these data, we calculated acceleration factors to quantify how much the pace of recent change needs to increase over this decade and then used these acceleration factors to classify indicators into one of five categories: heading in the right direction and on track, heading in the right direction but off track, heading in the right direction but well off track, heading in the wrong direction entirely, or insufficient data. But for a handful of indicators, namely those that directly track the adoption of innovative technologies, future change will likely follow an S-curve rather than a purely linear trajectory. To account for this rapid, nonlinear growth, we first considered the likelihood that future change in indicators will follow an S-curve and classified indicators as S-curve unlikely, S-curve possible, and S-curve likely. For "S-curve likely" indicators, we adjusted our methods for assessing progress made toward near-term targets. More specifically, we considered multiple lines of evidence, including the shape and stage of each indicator's S-curve, a review of the literature, and consultations with sectoral experts. We also fitted S-curves to historical data, where appropriate. In instances where we found compelling evidence of S-curve dynamics, we upgraded our assessment of progress from what it would have been based on a purely linear trendline. In this installment, for example, we upgraded the share of EVs in light-duty sales from "well off track" (the results of a purely linear assessment) to "on track," given ongoing exponential growth and projections of near-term change.

Finally, we also highlight recent developments—from adopting new policies to investing in the development of more nascent zero-carbon technologies to disbursing financial pledges—that have occurred primarily since the 26th Conference of the Parties (COP26) in Glasgow. For many of our 42 indicators, it can take time for actions undertaken by governments, civil society, and the private sector to spur global change. Yet these advances still represent meaningful progress made in the real-world economy, and they can offer insights into where momentum for positive change may be gaining traction, as well as where considerably more effort will be needed this decade to achieve 1.5°C-aligned targets. Thus, for each sector, we highlight recent developments across enabling conditions outlined in Boehm et al. (2022)—innovations in technologies, supportive policies, institutional strengthening, leadership, and shifts in behavior and social norms—to provide a more comprehensive snapshot of climate action. We focus primarily on those that are global in scope, though we also include those that are either from particularly important geographies or that represent promising (or worrying) developments.

Key findings across sectors

Heading into the first Global Stocktake, the world must face the hard truth that, while meaningful progress has been made across some sectors, collective efforts to first peak and then nearly halve GHG emissions this decade still fall woefully short. Recent rates of change for 41 of the 42 indicators across power, buildings, industry transport, forests and land, food and agriculture, technological carbon removal, and climate finance are not on track to reach their 1.5°C-aligned targets for 2030 (Figure ES-2). Worryingly, 24 of those indicators are well off track, such that at least a twofold acceleration in recent rates of change will be required to achieve their 2030 targets. Another 6 indicators are heading in the wrong direction entirely. Within this subset of lagging indicators, the most recent year of data represents a concerning worsening relative to recent trends for 3 indicators, with significant setbacks in efforts to eliminate public financing for fossil fuels, dramatically reduce deforestation, and expand carbon pricing systems. In 2021, for example, public financing for fossil fuels increased sharply, with government subsidies, specifically, nearly doubling from 2020 to reach the highest levels seen in almost a decade (OECD and IISD 2023). And in 2022, deforestation increased slightly to 5.8 million hectares (Mha) worldwide, losing an area of forests greater than the size of Croatia in a single year. Approximately 60 percent of these permanent losses occurred across humid tropical primary forests, among the world's most important landscapes for carbon sequestration and storage, as well as biodiversity (Hansen et al. 2013; Curtis et al. 2018; Turubanova et al. 2018; Tyukavina et al. 2022).

Amid this bad news, there are bright spots that underscore the possibility of rapid change. The recent rate of change for one indicator—the share of EVs in light-duty vehicle sales—is on track to achieve its 2030 target. Because EVs emit much less than fossil-fueled vehicles even when powered by dirty grids, achieving this target could go a long way toward decarbonizing road transport, which currently accounts for 11 percent of global GHG emissions. For another six indicators, global efforts are heading in the right direction at a promising, yet still insufficient pace. But with appropriate support and concerted actions, some of these indicators could experience rapid, nonlinear change in the coming years. Finally, of all indicators heading in the right direction, six indicators' most recent year of data represents a meaningful improvement over the previous historical trendline, with the greatest gains seen in efforts to mandate corporate climate risk disclosure, increase uptake of electric trucks, and expand the adoption of light-duty electric vehicles.

Still, an enormous acceleration in effort will be required across all sectors to get on track for 2030. A shift from business-as-usual, incremental change into emergency mode is now needed to deliver this level of required acceleration. The world, for example, needs to take the following steps:

- Dramatically increase growth in solar and wind power—the share of these two technologies in electricity generation has been growing by an annual average of 14 percent in recent years, but this needs to reach 24 percent to get on track for 2030.
- Phase out coal in electricity generation seven times faster—which is equivalent to retiring roughly 240 average-sized coal-fired power plants each year through 2030. And as countries continue to build coal-fired power plants, the number that must be retired each year will rise.
- Increase the coverage of rapid transit six times faster, with the top 50 highest-emitting cities collectively adding about 1,300 kilometers of metro rails, light-rail train tracks, and/or bus lanes per year throughout this decade.
- Reduce the annual rate of deforestation—equivalent to deforesting 15 football (soccer) fields per minute in 2022—four times faster.
- Shift to healthier, more sustainable diets eight times faster by lowering per capita consumption of ruminant meat (e.g., beef) to approximately two servings per week across high-consuming regions (Europe, the Americas, and Oceania). This shift does not require reducing consumption for populations who already consume below this target level, especially in low-income countries where modest increases in consumption can boost nutrition.
- Scale up global climate finance by nearly $500 billion per year throughout the remainder of this decade.

FIGURE ES-2 | Assessment of global progress toward 2030 targets

✓ **RIGHT DIRECTION, ON TRACK**

One indicator assessed exhibits a recent historical rate of change that is at or above the pace required to achieve its 2030 target.

! **RIGHT DIRECTION, OFF TRACK**

For **6 indicators**, the rate of change is heading in the right direction at a promising but insufficient pace to be on track for their 2030 targets.

✕ **RIGHT DIRECTION, WELL OFF TRACK**

For **24 indicators**, the rate of change is heading in the right direction at a rate well below the required pace to achieve their 2030 targets.

⮌ **WRONG DIRECTION, U-TURN NEEDED**

For **6 indicators**, the rate of change is heading in the wrong direction entirely.

? **INSUFFICIENT DATA**

For **5 indicators**, data are insufficient to assess the rate of change relative to the required action.

FIGURE ES-2 | Assessment of global progress toward 2030 targets (continued)

LIKELIHOOD OF FOLLOWING AN S-CURVE

ACCELERATION FACTOR[a]

N/A S-curve Likely

These indicators track technology adoption directly. They are either following an S-curve or are likely to do so in the future. For those in early stages of an S-curve, a meaningful increase may not occur immediately. Our assessment relies on author judgement of multiple lines of evidence.

5x S-curve Unlikely

These indicators are not closely related to technology adoption so are unlikely to follow an S-curve. Our assessment of progress relies on acceleration factors—calculations of how much recent rates of change (as estimated by linear trendlines) need to accelerate to achieve the 2030 targets.

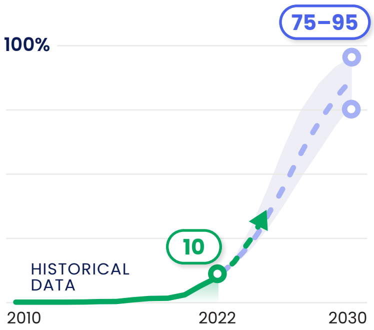
5x S-curve Possible

These indicators indirectly or partially track technology adoption so could experience non-linear change, although likely in a different form than an S-curve. Our assessment of progress relies on acceleration factors—calculations of how much recent rates of change (as estimated by linear trendlines) need to accelerate to achieve the 2030 targets. Change may occur faster than expected.

✓ RIGHT DIRECTION, ON TRACK

TRANSPORT N/A[b]

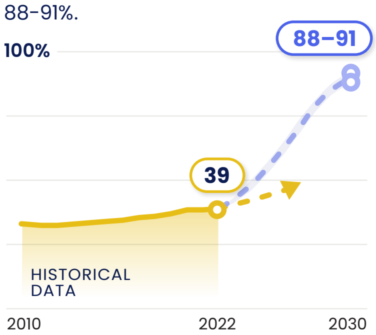
Increase the share of EVs to 75–95% of total annual LDV sales.



! RIGHT DIRECTION, OFF TRACK

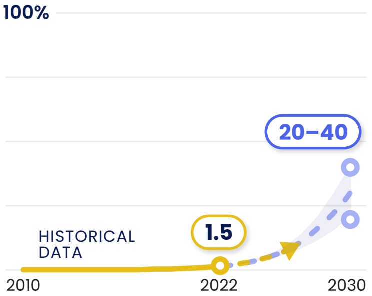
POWER N/A[b]

Increase the share of zero-carbon sources in electricity generation to 88–91%.



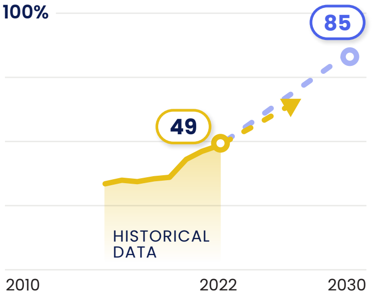
TRANSPORT N/A[b]

Expand the share of EVs to account for 20–40% of total LDV fleet.



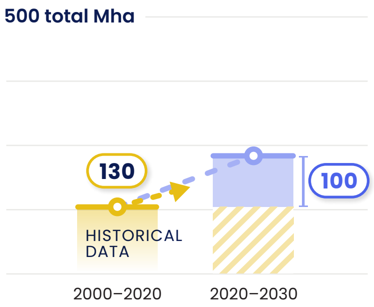
TRANSPORT N/A[b]

Increase the share of EVs to 85% of total annual two- and three-wheeler sales.



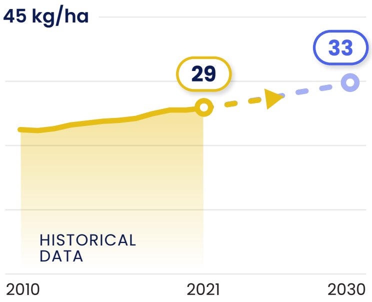
FORESTS AND LAND 1.5x

Reforest 100 Mha.



FOOD AND AGRICULTURE 1.2x

Increase ruminant meat productivity per hectare by 27%, relative to 2017.



FINANCE 1.5x

Increase the share of GHG emissions subject to mandatory corporate climate risk disclosures to 75%.

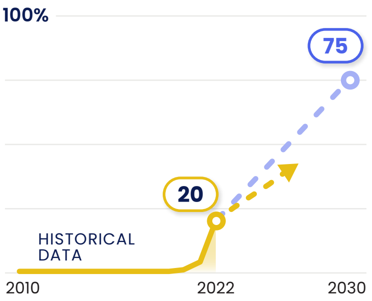
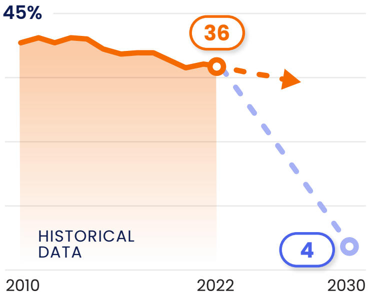


FIGURE ES-2 | Assessment of global progress toward 2030 targets (continued)

RIGHT DIRECTION, WELL OFF TRACK

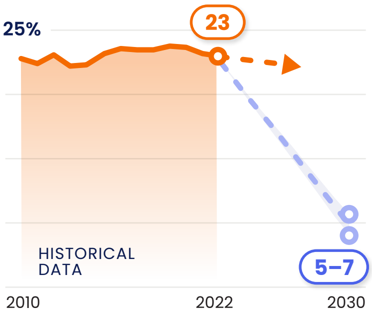
POWER 7x

Lower the share of coal in electricity generation to 4%.



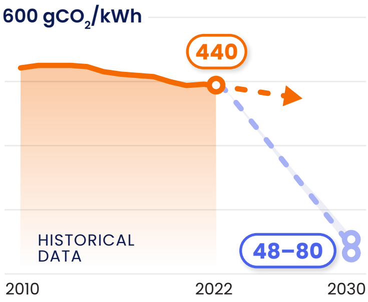
POWER >10x

Lower the share of unabated fossil gas in electricity generation to 5-7%.



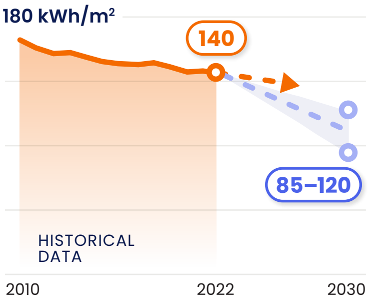
POWER 9x

Reduce the carbon intensity of electricity generation to 48-80 gCO_2/kWh.



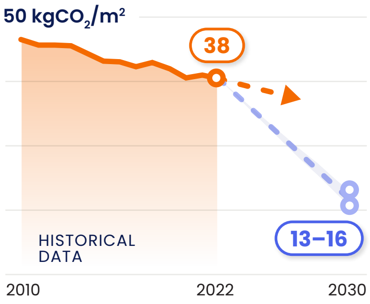
BUILDINGS 3x

Decrease the energy intensity of building operations to 85-120 kWh/m^2.



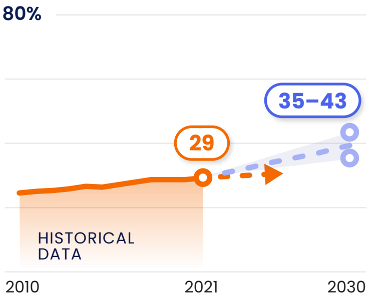
BUILDINGS 4x

Reduce the carbon intensity of building operations to 13-16 $kgCO_2/m^2$.



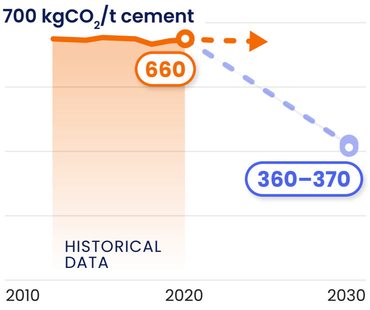
INDUSTRY 4x

Increase the share of electricity in the industry sector's final energy demand to 35-43%.



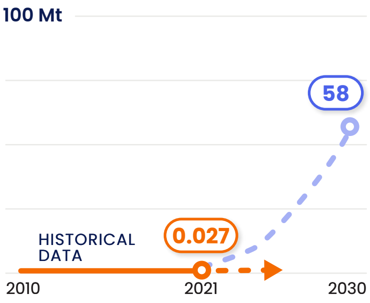
INDUSTRY >10x

Lower the carbon intensity of global cement production to 360–70 $kgCO_2/t$ cement by 2030.



INDUSTRY N/A[b]

Increase green hydrogen production capacity to 58 Mt.



TRANSPORT 6x

Double the coverage of public transport infrastructure across urban areas, relative to 2020.

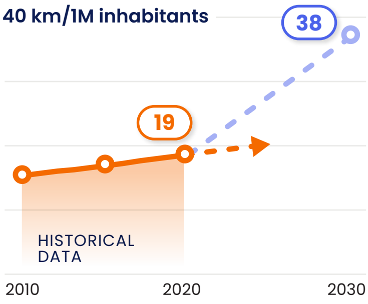
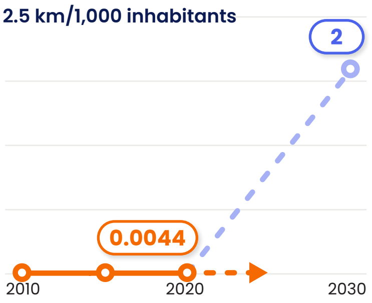


FIGURE ES-2 | Assessment of global progress toward 2030 targets (continued)

✕ **RIGHT DIRECTION, WELL OFF TRACK**

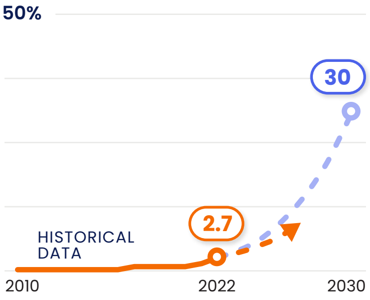
TRANSPORT >10x

Reach 2 km of high-quality bike lanes per 1,000 inhabitants across urban areas.



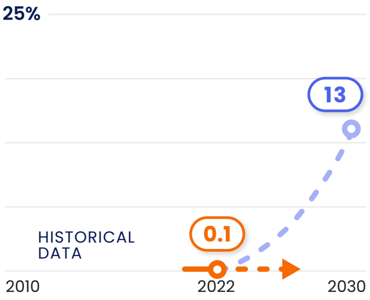
TRANSPORT N/A[b]

Increase the share of BEVs and FCEVs to 30% of total annual MHDV sales.



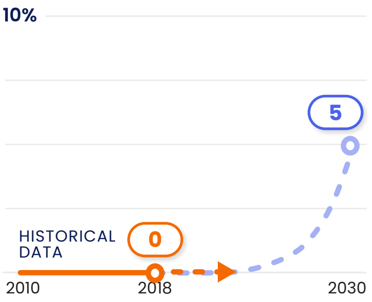
TRANSPORT N/A[b]

Increase the share of sustainable aviation fuels in global aviation fuel supply to 13%.



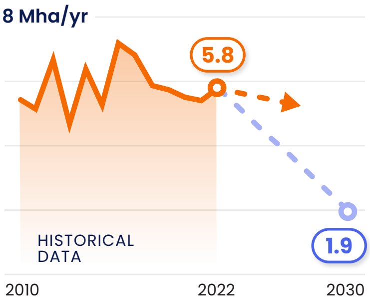
TRANSPORT N/A[b]

Increase the share of zero-emissions fuel in maritime shipping fuel supply to 5%.



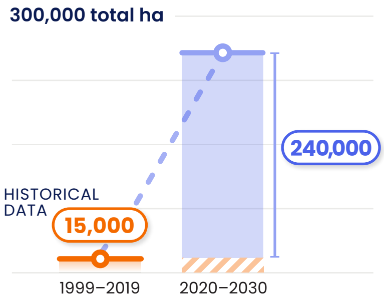
FORESTS AND LAND 4x

Reduce the annual rate of gross deforestation to 1.9 Mha/yr.



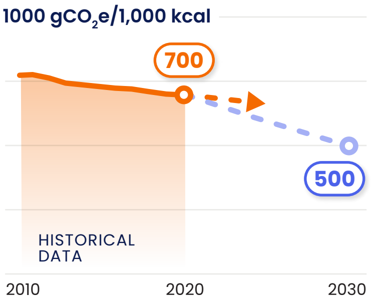
FORESTS AND LAND >10x

Restore 240,000 ha of mangroves.



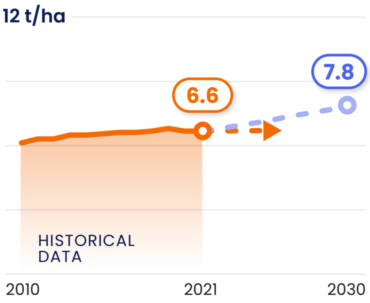
FOOD AND AGRICULTURE 3x

Reduce the GHG emissions intensity of agricultural production by 31%, relative to 2017.



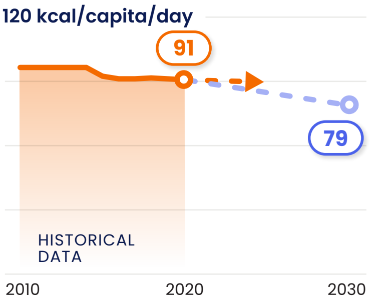
FOOD AND AGRICULTURE >10x

Increase crop yields by 18%, relative to 2017.



FOOD AND AGRICULTURE 8x

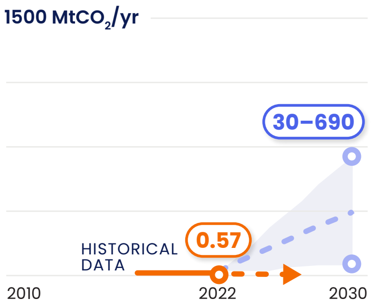
Reduce ruminant meat consumption in high-consuming regions to 79 kcal/capita/day.



RIGHT DIRECTION, WELL OFF TRACK

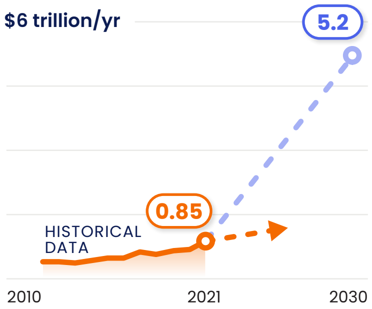
TECHNOLOGICAL CARBON REMOVAL >10x

Scale up the annual rate of technological carbon removal to 30-690 MtCO$_2$/yr.



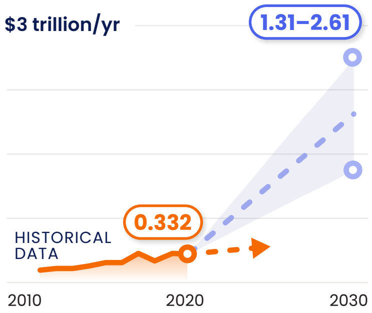
FINANCE 8x

Increase global climate finance flows to US$5.2 trillion/yr.



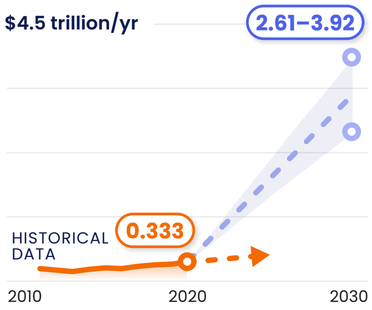
FINANCE 8x

Increase global public climate finance flows to $1.31–2.61 trillion/yr.



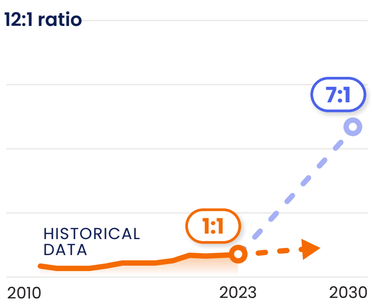
FINANCE >10x

Increase global private climate finance flows to $2.61–3.92 trillion/yr.



FINANCE >10x

Increase the ratio of investment in low-carbon to fossil fuel energy supply to 7:1.



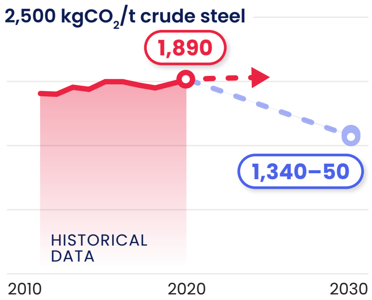
FINANCE >10x

Raise the weighted average carbon price to $170-290/tCO$_2$e.

WRONG DIRECTION, U-TURN NEEDED

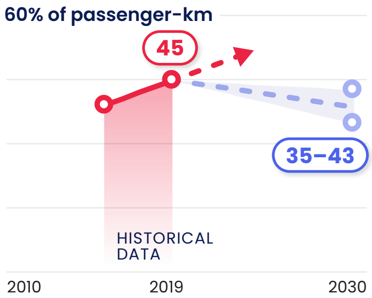
INDUSTRY U-turn needed

Lower the carbon intensity of global steel production to 1,340–50 kgCO$_2$/t crude steel.



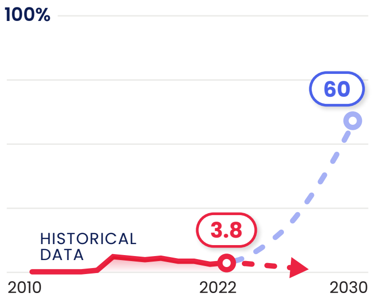
TRANSPORT U-turn needed

Reduce the percentage of trips made in passenger cars to 35-43%.



TRANSPORT U-turn needed[b]

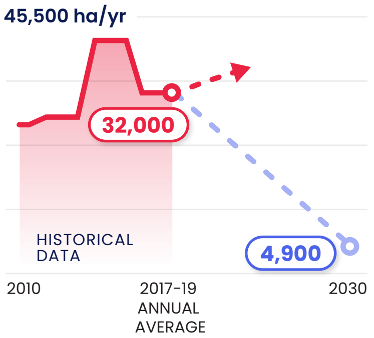
Increase the share of BEVs and FCEVs to 60% of total annual bus sales.



WRONG DIRECTION, U-TURN NEEDED

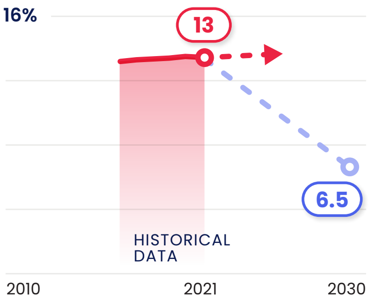
FORESTS AND LAND U-turn needed

Reduce the annual rate of gross mangrove loss to 4,900 ha/yr.



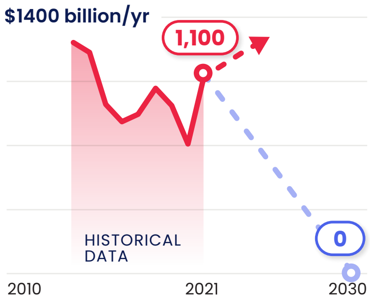
FOOD AND AGRICULTURE U-turn needed

Reduce the share of food production lost by 50%, relative to 2016.



FINANCE U-turn needed

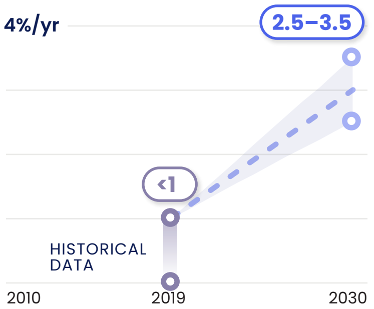
Phase out public financing for fossil fuels, including subsidies.



INSUFFICIENT DATA

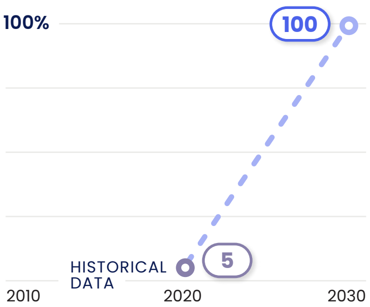
BUILDINGS Ins. data

Increase the annual retrofitting rate of buildings to 2.5-3.5%/yr.



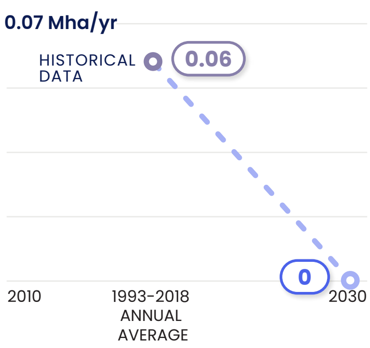
BUILDINGS Ins. data

Ensure all new buildings are zero-carbon in operation.



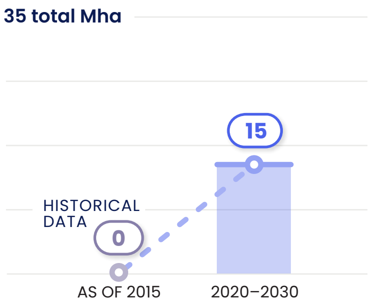
FORESTS AND LAND Ins. data

Reduce the annual rate of peatland degradation to 0 Mha/yr.



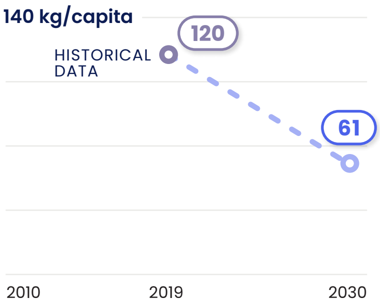
FORESTS AND LAND Ins. data

Restore 15 Mha of degraded peatlands.



FOOD AND AGRICULTURE Ins. data

Reduce per capita food waste by 50%, relative to 2019.



Notes: BEV = battery electric vehicle; EV = electric vehicle; FCEV = fuel cell electric vehicle; gCO_2/kWh = grams of carbon dioxide per kilowatt-hour; gCO_2e/1,000 kcal = grams of carbon dioxide equivalent per 1,000 kilocalories; GHG= greenhouse gas; ha/yr = hectares per year; kcal/capita/day = kilocalories per capita per day; kg/capita = kilograms per capita; $kgCO_2/m^2$ = kilogram of carbon dioxide per square meter; $kgCO_2$/t = kilograms of carbon dioxide per tonne; kg/ha = kilograms per hectare; km/1M inhabitants = kilometers per 1 million inhabitants; km/1,000 inhabitants = kilometers per 1,000 inhabitants; kWh/m^2 = kilowatt-hour per square meter; LDV = light-duty vehicle; Mha/yr = million hectares per year; MHDV = medium- and heavy-duty commerical vehicle; Mt = million tonnes; $MtCO_2$/yr = million tonnes of carbon dioxide per year; passenger-km = passenger-kilometers; tCO_2e = tonne of carbon dioxide equivalent; t/ha = tonnes per hectare; yr = year. For more information on indicators' definitions, deviations from our methodology to assess progress, and data limitations, see corresponding indicator figures in each section.

[a] For acceleration factors between 1 and 2, we round to the 10th place (e.g., 1.2 times); for acceleration factors between 2 and 3, we round to the nearest half number (e.g., 2.5 times); for acceleration factors between 3 and 10, we round to the nearest whole number (e.g., 7 times); and acceleration factors higher than 10, we note as >10. See data underlying these calculations in *Appendix A*.

[b] For indicators categorized as S-curve likely, acceleration factors calculated using a linear trendline are not presented, as they would not accurately reflect an S-curve trajectory. The category of progress was determined based on author judgment, using multiple lines of evidence. See corresponding indicator figures in each section, Appendix C, and Jaeger et al. (2023) for more information.

Source: Authors' analysis based on data sources listed in each section.

Key findings by sector

Power

- ! Share of zero-carbon sources in electricity generation (%)
- ✕ Share of coal in electricity generation (%)
- ✕ Share of unabated fossil gas in electricity generation (%)
- ✕ Carbon intensity of electricity generation (gCO_2/kWh)

In 2022, CO_2 emissions from electricity generation reached a record high, but rapid growth in both renewable energy installation and generation suggests that power sector emissions may have peaked (Wiatros-Motyka et al. 2023). These recent changes suggest that the transformational changes needed to decarbonize the power sector globally—including shifting to zero-carbon power sources, as well as phasing out coal and unabated fossil gas in electricity generation—are taking off. Still, this progress must accelerate even faster to keep the Paris Agreement's 1.5°C limit within reach, as none of the power sector indicators are yet on track to achieve their 2030 targets.

Recent efforts made in scaling up renewable power sources have progressed far faster than those dedicated to phasing out fossil fuel electricity generation. Zero-carbon technologies, such as solar and wind power, are widely mature and commercialized, with manufacturing capacity increasing as the cost of renewable energy and complementary energy storage technologies continue to plummet at unprecedented rates. Solar photovoltaics and onshore wind are now the cheapest sources of new-build generation for at least two-thirds of the global population (BloombergNEF 2020), and recent years have witnessed record-breaking growth in adoption of these technologies, with strong evidence of ongoing exponential growth for solar. In 2022, for example, growth in wind and solar generation (+560 TWh) alone met 80 percent of all global electricity demand growth (+690 TWh) (Wiatros-Motyka et al. 2023). Some of the fastest growth in the share of renewable power generation has been seen in developing countries such as Namibia, Uruguay, Palestine, and Jordan, where wind and solar scale-up is also helping to increase energy security and access (Jaeger 2023). However, achieving such successes across all countries, and particularly lower-income nations, will require a dramatic scale-up in finance, as investments in zero-carbon power lag far behind needs.

Decarbonizing power will also require rapid declines in fossil fuel generation. As countries debate whether to phase coal "down" or "out," roughly 2,100 GW of coal-fired power stations are in operation, and approximately 560 GW of new coal-fired power stations are in the pipeline, with most new coal projects planned for developing countries like China, India, Indonesia, and Bangladesh (GEM 2023a; 2023b). These plants will need to be retired early to phase out coal globally by 2040, with a phase-out of unabated fossil gas following very soon afterward to avoid locking the world into high GHG emissions for decades. While progress is lagging, promising examples demonstrate the potential to drastically reduce fossil fuel power usage. In 2012, about 40 percent of the electricity generated in the United Kingdom came from coal. Today, that figure is just 2 percent (Ember 2023). As countries follow suit and work to wean themselves from coal, as well as from fossil gas, retraining and compensating workers will prove critical to ensuring a more just and equitable transition (World Bank n.d.).

Buildings

- ✕ Energy intensity of building operations (kWh/m^2)
- ✕ Carbon intensity of building operations (kgCO$_2$/m$_2$)
- ? Retrofitting rate of buildings (%/yr)
- ? Share of new buildings that are zero-carbon in operation (%)

After rising steadily over the past three decades, global emissions from buildings have roughly stabilized since 2018 (IEA 2023j). Further decarbonization of the buildings sector globally will require a multipronged strategy focused on improving the energy efficiency within buildings, decarbonizing the remaining energy used, retrofitting the existing building stock, and ensuring that new buildings are constructed to be zero-carbon in operation. Additionally, emissions generated during the construction of buildings need to be rapidly reduced and the use of fluorinated gases with high global warming potential for cooling systems, which has been increasing, needs to reverse course entirely (UNEP and IEA 2020; Velders et al. 2022).

Although publicly available data indicate the world is not yet on track to deliver any of these much-needed changes by 2030, a recent uptick in building regulations, especially in the European Union, suggests that some progress is underway. Regulation remains an effective tool for aligning the buildings sector with the Paris Agreement's 1.5°C temperature limit (Boehm et al. 2022; IEA 2021d; Economidou et al. 2020), and in some countries the ongoing energy crisis has prompted more robust regulations aimed at phasing out fossil fuel consumption in the buildings sector. This year, for example, the European Union proposed updates to its Energy Performance of Buildings Directive, which include banning the use of fossil fuels for heating in new buildings and those undergoing renovation, as well as requiring a complete phaseout of these fossil fuels for heating by 2035 (European Parliament 2023a). Though not yet adopted, this proposal represents a significant step forward, as it is raising the ambition of mitigation in the buildings sector in a key geography. Similarly, sales of heat pumps—a technology that enables the decarbonization of heating in buildings—continued to increase, rising by 120 percent in Poland, 38 percent in Europe, and 11 percent globally in 2022 (Rosenow and Gibb 2023; Monschauer et al. 2023). Such progress now needs to spread globally, with more national governments, cities, and businesses setting targets for decarbonizing buildings and establishing robust implementation plans that put those targets in good stead.

Industry

- ✕ Share of electricity in the industry sector's final energy demand (%)
- ✕ Carbon intensity of global cement production (kgCO$_2$/t cement)
- ✕ Green hydrogen production (Mt)
- ⇩ Carbon intensity of global steel production (kgCO$_2$/t crude steel)

Since 2000, total GHG emissions from industry have increased faster than in any other sector (Minx et al. 2021). But transforming the global industrial system from one where emissions are still growing to one aligned with limiting warming to 1.5°C with no or limited overshoot is possible. Such a transition will first require reducing the need for new industrial products by increasing circularity and lowering consumption. Improving energy efficiency across industrial processes, as well as electrifying those that rely on low- and medium-temperature heat, will also prove instrumental to decarbonizing the sector. Yet not all industrial processes can be easily electrified, and new solutions will likely be needed to reduce GHG emissions from chemical reactions and high-heat industrial processes, particularly for steel and cement. Additionally, combining conventional technologies with carbon capture and utilization (CCU) and carbon capture and storage (CCS) will also play a small role in balancing remaining process and high-temperature heat emissions from the sector.

While none of the industry indicators are on track, recent developments—from increased investment in industrial decarbonization to new supportive policies to recently announced projects—invite optimism. For example, in 2022, the International Finance Corporation, the largest global development institution focused on the private sector in emerging markets, made its first green loan for material manufacturing in Africa to Senegal's leading cement manufacturer (IFC 2023a), and India, home to one of the world's fastest-growing industry sectors, announced the establishment of a carbon market scheme for aluminum and cement manufacturers, petroleum refineries, and steel (Munjal 2022; IEA 2021e), which can help accelerate decarbonization of those industries. Recent years have also witnessed the global steel capacity pipeline shift from production technologies that rely on coal to less emissions-intensive plants, with 28 new green hydrogen–related direct reduced iron steel projects announced between 2021 and 2022 alone (authors' calculations based on data from the Green Steel Tracker 2023). And according to the International Energy Agency (IEA 2022h), global installed electrolyzer capacity grew by 23 percent from 2021 to

2022, reaching roughly 690 megawatts (MW). These promising developments now need to be significantly scaled and accelerated around the globe to meet industrial decarbonization targets this decade.

Transport

- ✕ Share of electric vehicles in light-duty vehicle sales (%)
- ! Share of electric vehicles in the light-duty vehicle fleet (%)
- ! Share of electric vehicles in two- and three-wheeler sales (%)
- ✕ Number of kilometers of rapid transit per 1 million inhabitants (km/1M inhabitants)
- ✕ Number of kilometers of high-quality bike lanes per 1,000 inhabitants (km/1,000 inhabitants)
- ✕ Share of battery electric vehicles and fuel cell electric vehicles in medium- and heavy-duty commercial vehicle sales (%)
- ✕ Share of sustainable aviation fuels in global aviation fuel supply (%)
- ✕ Share of zero-emissions fuels in maritime shipping fuel supply (%)
- ⇩ Share of kilometers traveled by passenger cars (% of passenger-km)
- ⇩ Share of battery electric vehicles and fuel cell electric vehicles in bus sales (%)

After industry, transport—including road, rail, sea, and air travel—remains the world's second-fastest-growing source of GHG emissions (Minx et al. 2021; European Commission and JRC 2022; IEA 2022i). Transforming this sector to mitigate climate change will require a number of interconnected shifts. First, bringing jobs, services, and goods closer to where people live can help avoid some motorized travel altogether. At the same time, the world must shift away from vehicle trips to shared, collective, or active transport modes including public transportation, walking, and cycling. Crucially, electric vehicles must quickly replace the internal combustion engine, and for those modes of transport that cannot easily be electrified, such as shipping and aviation, meeting Paris-aligned targets requires the scale-up of zero-emissions fuels where modal shifts are not possible.

Yet progress in accelerating these transformational changes remains uneven. Global efforts to electrify common modes of road transport, such as light-duty vehicles and two- and three-wheelers, are heading in the right direction, with recent rates of change unfolding either at the pace required to achieve near-term targets or at a promising, though still, insufficient speed for these indicators. But shifting to more sustainable modes of transit and decarbonizing longer-haul transport like trucking, shipping, and aviation have proven more difficult, with all indicators either well off track or heading in the wrong direction entirely.

In one bright spot this year, the share of electric vehicles in light-duty vehicle sales is on track for the first time. The 2030 target is well in sight as these vehicles become cheaper, ranges improve, and charging infrastructure is built out. In addition to continued technology cost declines, major policy updates, including the Inflation Reduction Act in the United States and updates to the European Union Green Deal, are aimed at helping push EV sales into overdrive. This growth is largely limited to China, Europe, and the United States, with additional efforts needed to extend this opportunity to developing countries.

Recent progress made in scaling up two- and three-wheelers, bicycles, and maritime shipping also suggests that transformational changes beyond car sales may be on the horizon. The share of electric vehicles in two- and three-wheeler sales increased from 34 percent in 2015 to 49 percent in 2022 (BloombergNEF 2023a)—thanks in large part to subsidies and demand incentives for three-wheelers in India (IEA 2023e)—and that global share could hit 85 percent in 2030 if more growth occurs outside of China and India. Some jurisdictions are also scaling efforts to avoid motorized travel. Bogotá, Colombia, for example, added 84 kilometers of new, permanent bike lanes during the COVID-19 pandemic to its more than 547 existing kilometers to provide safe and nonpolluting ways to get around the city (Ramírez 2021). And, at the International Maritime Organization, countries agreed to a new GHG strategy that aims to cut emissions from maritime shipping by 20–30 percent in 2030 and 70–80 percent in 2040 (Smith and Shaw 2023). This includes a target to reach 5 percent "zero or near zero GHG emission technologies" by 2030, a target tracked in this report (IMO 2023).

Forests and land

! Reforestation (total Mha)

✕ Deformation (Mha/yr)

✕ Mangrove restoration (total ha)

⇩ Mangrove loss (ha/yr)

? Peatland degradation (Mha/yr)

? Peatland restoration (total Mha)

Accounting for nearly a fifth of net anthropogenic GHG emissions globally in 2021, agriculture, forestry, and other land uses is the only sector that serves as both a source and a sink of GHGs (Minx et al. 2021; European Commission and JRC 2022). The loss and degradation of ecosystems—particularly forests, peatlands, and mangroves—release GHGs into the atmosphere, while protecting, restoring, and sustainably managing these same ecosystems can lower GHG emissions, enhance carbon sequestration, and build resilience to climate impacts (IPCC 2019, 2022b). If implemented appropriately, these land-based mitigation measures can not only help limit warming to 1.5°C (Roe et al. 2019, 2021) but also deliver substantial benefits to sustainable development, adaptation, and biodiversity—from regulating water quality to provisioning food to sustaining clean air (IPCC 2019, 2022b; IPBES 2019; UNCCD 2017). But despite the clear benefits of action, global efforts to scale up land-based mitigation measures fall well short of the required ambition for 2030 and 2050.

Protecting these high-carbon ecosystems can deliver the lion's share of mitigation across land-based measures, but collective progress made in virtually halting loss and degradation remains far from promising. Together, the world's forests, peatlands, and mangroves hold well over 1,000 GtC (Pan et al. 2011; Temmink et al. 2022), and by one estimate, roughly a third or less of these carbon stocks (~340 GtC) are vulnerable to human disturbances, such that they would be released into the atmosphere following conversion or degradation (Noon et al. 2021). Some of these carbon losses can occur quite rapidly, and if released, much of this carbon would be difficult for ecosystems to recover on timescales relevant to reaching net-zero CO_2 emissions by midcentury (Goldstein et al. 2020; Cook-Patton et al. 2021; Noon et al. 2021). Instead, fully rebuilding lost carbon stocks would take 6 to 10 decades for forests, well over a century for mangroves, and centuries to millennia for peatlands (Goldstein et al. 2020; Temmink et al. 2022). It is alarming, then, that deforestation has occurred across 48 Mha since 2015, that 57 Mha of peatlands are currently degrading, and that the world's shorelines have lost 560,000 hectares of mangroves since 1999 (Hansen et al. 2013; Curtis et al. 2018; Turubanova et al. 2018; Tyukavina et al. 2022; UNEP 2022b; Murray et al. 2022).

Limiting global warming to 1.5°C will also require large-scale restoration, but, here too, global efforts must accelerate significantly. Getting on track for 2030 will require the world to reforest another 100 Mha, as well as restore 15 Mha of degraded peatlands and 240,000 hectares of mangroves. Critically, appropriately implemented restoration can complement, but not replace, efforts to protect the world's remaining forests, peatlands, and mangroves.[3] Not only is recovering these ecosystems often more costly than safeguarding them, but it may also take decades (if not longer) for these ecosystems to regain species diversity, ecosystem structure, and ecological functions, all of which may impact carbon cycling and GHG fluxes within these ecosystems (Sasmito et al. 2019; Poorter et al. 2021; Kreyling et al. 2021; Su et al. 2021; Cook-Patton et al. 2021; Loisel and Gallego-Sala 2022). Restoring ecosystems, while needed to mitigate climate change, does not offer a one-to-one trade with protecting them.

However, a slate of recent developments—from new multilateral commitments on conserving ecosystems to major policy shifts in key countries—offers some good news, particularly for the world's forests. Since COP26, for example, more than 140 countries have pledged to halt and reverse forest loss and degradation under the Glasgow Leaders' Declaration on Forests and Land Use; nearly 190 Parties adopted the Kunming-Montreal Biodiversity Framework, which commits signatories to protecting 30 percent of the planet and restoring another 30 percent of degraded ecosystems by 2030; within days of his inauguration, President Luiz Inácio Lula da Silva undertook a range of actions to combat deforestation across the Brazilian Amazon; in light of Indonesia's success in maintaining historically low levels of deforestation, the Southeast Asian nation and Norway signed another REDD+ deal; and the European Union recently adopted a new regulation to combat deforestation and forest degradation associated with forest commodities. While these signals of change are promising, history must not repeat itself. Interim targets made under commitments to protect and restore the world's high-carbon ecosystems, such as the New York Declaration on Forests and the Bonn Challenge, have been missed, while promised funds, including international REDD+ finance, have yet to fully materialize.

Food and agriculture

- ! Ruminant meat productivity (kg/ha)
- × GHG emissions intensity of agricultural production (gCO_2e/1,000 kcal)
- × Crop yields (t/ha)
- × Ruminant meat consumption (kcal/capita/day)
- ⇩ Share of food production lost (%)
- ? Food waste (kg/capita)

GHG emissions from agricultural production across both croplands and pastures remain a significant, still-growing contributor to global GHG emissions (Minx et al. 2021; European Commission and JRC 2022). As the world's population climbs from roughly 8 billion in 2023 to nearly 10 billion by 2050 (UNDESA 2022), feeding more people more nutritiously, while advancing socioeconomic development, conserving natural ecosystems, and reducing agricultural emissions will prove enormously difficult. Transforming the world's food and agriculture sector to address these challenges will require a combination of supply- and demand-side shifts. Halving food loss and waste in all regions, as well as reducing consumption of ruminant meat (e.g., beef) in high-consuming regions, can help curb GHG emissions from both agricultural production and associated land-use changes like deforestation. Shifts in on-farm practices, as well as the research, development, and deployment of new food and agriculture technologies, will also be needed to sustainably produce more food on existing agricultural lands—thereby halting farms' expansion into high-carbon, biodiverse ecosystems like forests and peatlands—and to ensure long-term productivity as well. These changes to agricultural production must simultaneously lower the amount of GHGs emitted per kilocalorie of food, safeguard soil and water resources, and build resilience to climate change.

Global efforts to reduce emissions from food production and consumption, while tackling food insecurity, malnutrition, and hunger, have yet to progress at a pace and scale commensurate with these challenges. With the most recent year of COVID-era data available (2020 or 2021 depending on the indicator), the overall global picture shows that progress in the food and agriculture sector remains far too slow. Improvements in agricultural GHG emissions intensity, livestock production efficiency, and crop yields—while encouraging—are not yet keeping pace with continued global growth in demand for food. The global rate of food loss slightly decreased between 2020 and 2021 but remains higher than the baseline year of 2016 (FAOSTAT 2023). And demand-side changes to consumption patterns, particularly among the highest-consuming regions, need to accelerate as well. If the footprint of croplands and pasturelands continue to expand into tropical forests and peatlands and GHG emissions from food production continue to grow, the global goals of eliminating deforestation and peatland degradation, restoring hundreds of millions of hectares of deforested and degraded lands, and limiting global warming to 1.5°C will become even harder to reach. The world urgently needs to accelerate efforts to create a sustainable food future.

Although efforts to mitigate GHG emissions across the food and agriculture sector are well behind the pace and scale needed to keep warming below 1.5°C, there are signs of positive changes on both the supply and demand sides. For example, dozens of countries have committed to accelerating agricultural innovation through the Agriculture Innovation Mission for Climate, cities have committed to supporting dietary shifts and reductions in food loss and waste through a variety of initiatives like the C40 Cities' Good Food Cities Accelerator, and major food service providers have made measurable progress serving more climate-friendly meals through the Coolfood Pledge. Simultaneously, the Breakthrough Agenda, the Glasgow Leaders' Declaration on Forests and Land Use, and the Global Methane Pledge—all announced at COP26—and the Kunming-Montreal Global Biodiversity Framework adopted in December 2022 reflect growing political attention to the crucial role that the food and agriculture sector has to play in combatting the climate crisis. But the resources and enabling conditions needed to follow through on these global pledges, from finance to policy to technologies, have yet to fully materialize.

Technological carbon removal

- × Technological carbon removal ($MtCO_2$/yr)

In addition to deep and rapid GHG emissions reductions, all pathways that limit warming to 1.5°C also rely on carbon dioxide removal (IPCC 2022b). Referred to as "carbon removal" in this report, this includes both land-based approaches (Forests and Land Indicators 4–6) and technological approaches. But efforts to rapidly scale up these carbon removal technologies remain well off track, with less than 1 million tonnes of carbon dioxide ($MtCO_2$) removed and permanently stored each year. This is equivalent to less than 1 percent of the amount of technological carbon removal likely needed annually by 2030.

Over the last five years, technological carbon removal approaches have shifted from a niche concept to a common component of climate action portfolios, supported by billions of dollars in public and private funding (Frontier 2023; U.S. Congress 2021). In the United States, for example, the 2021 Bipartisan Infrastructure Law provided $3.5 billion to build four direct air capture (DAC) hubs each with capacity to remove 1 $MtCO_2$/year, and the 2022 Inflation Reduction Act more than tripled the tax credit that DAC receives (U.S. Congress 2021; U.S. Senate 2022b). In 2022, the European Commission launched its proposal for a Carbon Removal Certification Framework, the first public sector voluntary certification framework for high-quality carbon removal. Momentum is also building in the private sector to scale up development and deployment of technological carbon removal. A coalition of companies, including Stripe and Shopify, launched Frontier in 2022, a commitment to buy $925 million worth of carbon permanently captured and removed from the atmosphere between 2022 and 2030. In 2023, more companies joined the commitment, bringing the total to more than $1 billion in pledged future carbon removal purchases (Frontier 2023).

But, alongside this momentum, challenges in scaling up technological removal approaches rapidly and responsibly remain. More public funding for research, development, and demonstration is needed to help develop a broad portfolio of carbon removal approaches to balance the risks and trade-offs of each; greater deployment support is needed; greater demand from carbon removal purchasers is needed to spur market growth; attention to measurement, reporting, and verification is needed to ensure credibility and consistency in tracking removals; and governance gaps at all levels need to be addressed to ensure that scale-up happens sustainably and equitably.

Finance

- ! Share of global GHG emissions under mandatory corporate climate risk disclosure (%)
- ✗ Global total climate finance (trillion $/yr)
- ✗ Global public climate finance (trillion $/yr)
- ✗ Global private climate finance (trillion $/yr)
- ✗ Ratio of investment in low-carbon to fossil fuel energy supply
- ✗ Weighted average carbon price in jurisdictions with emissions pricing systems (2015$/$tCO_2e$)
- ⇩ Total public financing for fossil fuels (billion $/yr)

Finance is a vital enabler of climate action, but current investment patterns are hindering the pace and scale of the transition to net-zero economies. Transforming the global financial system to support ambitious climate action will require scaling up climate finance in all countries and from both public and private actors, as well as ensuring that all financial flows are consistent with the Paris Agreement's goals. Such alignment includes ensuring a much higher ratio of investment in low-carbon energy compared to fossil fuels; more transparently measuring, reporting, and managing climate risks; accounting for the full climate costs of GHG emissions through carbon pricing mechanisms; and ending public financing for fossil fuels.

Efforts to dramatically increase climate investment remain far too slow, with the need for increased funding particularly acute in developing countries. Global climate finance flows reached an all-time high in 2021 of $850 billion to $940 billion, representing at least a 27 percent increase from 2020 (Naran et al. 2022). But growth in climate investment remains well off track from reaching the $5.2 trillion per year needed globally by 2030. After this report went through peer review, Buchner et al. (2023) published data that show significant increases in total global climate finance. Flows reached $1.1 trillion in 2021 and $1.4 trillion in 2022. But even with these gains, substantial increases will be required by 2030. For developing countries, specifically (excluding China), the Independent High-Level Expert Group on Climate Finance estimates that they need $2 trillion to $2.8 trillion in investment in mitigation and adaptation per year by 2030, and that $1 trillion of this would need to come from external sources (Songwe et al. 2022). Yet at present, climate investment in developing countries is around a 10th of this (Naran et al. 2022; OECD 2022a).

Failure to simultaneously phase out investments in high-emissions activities will likely place the 1.5°C limit out of reach—and, here too, progress remains inadequate. While the clean energy economy is beginning to replace the fossil economy, this transition is not occurring rapidly enough. The war in Ukraine has caused oil and gas prices to spike, and in response fossil fuel consumption subsidies reached $1 trillion in 2022—the highest level ever (IEA 2023c). Efforts to expand carbon pricing systems also appear stalled, with no significant increase in global GHG emissions covered since 2021 (World Bank 2023d). The political backlash in the United States against sustainable finance and the allocation of investments based on climate considerations poses a threat to aligning private climate finance with the Paris Agreement's goals. Nonetheless, one bright spot is the growing trend of governments mandating corporate disclosure of climate risks, with countries representing about 20 percent of global GHG emissions having done so as of 2022 (TCFD 2022; Wu and Uddin 2022; Naik 2021). A recent major development was the approval of the European Union's Corporate Sustainability Reporting Directive that will require reporting on a wide range of sustainability disclosures (European Parliament 2022). Failure to align finance with climate goals risks delaying action across all other sectors.

SECTION 1

Methodology for Assessing Progress

This section provides a summary of this report's methodology. Please see Jaeger et al. (2023), the accompanying technical note, for a more detailed explanation of our selection of sectors, targets, indicators, and datasets, as well as our methods for assessing progress toward 1.5°C-aligned targets.

Selection of sectors, targets, and indicators

In modeled pathways that limit global temperature rise to 1.5°C above preindustrial levels with no or limited overshoot,[4] greenhouse gas (GHG) emissions peak immediately or before 2025 at the latest, and then fall by a median of 43 percent by 2030 and 60 percent by 2035, relative to 2019 (IPCC 2022b, 2023). By around midcentury, carbon dioxide (CO_2) emissions reach net zero in these pathways. Achieving such deep GHG emissions reductions, the Intergovernmental Panel on Climate Change (IPCC) finds, will require rapid transformations across all major sectors—power, buildings, industry, transport, forests and land, and food and agriculture[5]—as well as the immediate scale-up of climate finance and of carbon removal technologies to compensate for the residual GHG emissions that will likely prove difficult to eliminate (IPCC 2022b).

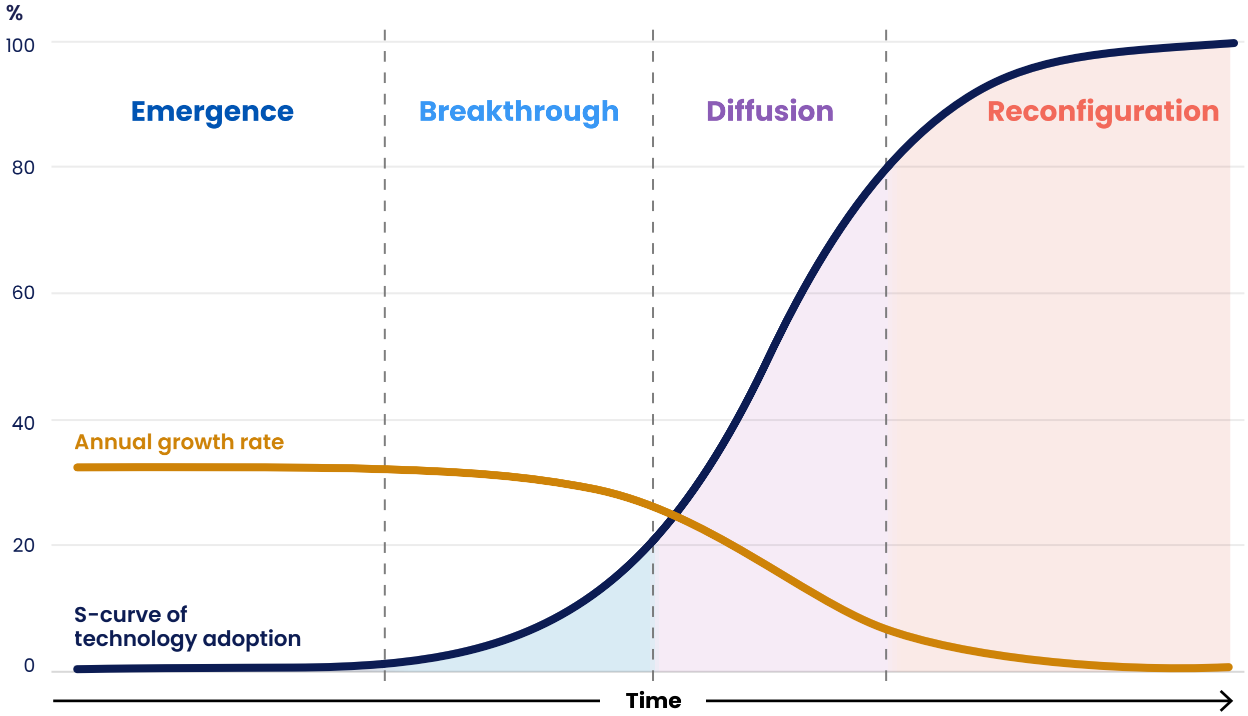
In the *State of Climate Action* series, we translate the far-reaching transformations needed to achieve the Paris Agreement's 1.5°C global temperature limit into a more manageable set of shifts for each sector that, taken together, can help overcome the deep-seated carbon lock-in common to them all (Seto et al. 2016). We also identify changes that must occur to support the rapid scale-up of carbon removal technologies and climate finance. The global food and agriculture sector, for example, needs to transform from its current state into one that can nutritiously feed nearly 10 billion people while lowering GHG emissions, safeguarding biodiversity, and halting the expansion of agricultural production, particularly across high-carbon ecosystems. To achieve this sectoral transformation, multiple shifts must occur—the world must achieve significant gains in cropland and livestock productivity, dramatically reduce food loss and waste, limit the overconsumption of ruminant meat, and accelerate declines in the GHG emissions intensity of agricultural production processes, such as rice cultivation, enteric fermentation, and chemical fertilizer application. Almost all of these shifts must happen simultaneously to secure a sustainable food future. However, the sectoral shifts we identify in this report, including those beyond the food and agricultural sector, do not provide a comprehensive roadmap to limiting warming to 1.5°C; rather, they form a set of priority actions needed to achieve this temperature goal.[6]

For each shift featured in this report, we established global near-term and long-term targets—typically for 2030 and 2050, respectively—that are aligned with pathways limiting global temperature rise to 1.5°C with no or limited overshoot. We also identified interim targets for 2035 and 2040 where possible. Although we do not systematically consider equity or biodiversity impacts in our target selection,[7] we do apply additional criteria wherever feasible and appropriate, such as cost-effectiveness or environmental and social safeguards. For each set of near-term and long-term targets, we then selected corresponding indicators with historical data to assess global progress made toward these sectoral mitigation goals. An example of a near-term target would be halving food waste by 2030, relative to 2019, while its corresponding indicator would be kilograms of food waste per capita per year. Methods for selecting all indicators and targets are described further in Jaeger et al. (2023).

Assessment of global progress

We provide a snapshot of global progress made toward limiting warming to 1.5°C by assessing whether each indicator is on track to reach its near-term target. To do so, we collected historical data for each indicator, relying on datasets that are open, independent of bias, reliable, and consistent. We strove to use the most recent data, but there is often a time lag before data become available (between one and three years for most indicators, but roughly five years for some). As a result, the year of most recent data varies among indicators. In some

FIGURE 1 | Illustration of an S-curve



Exponential growth
Although annual growth rates are high, the S-curve appears flat since its starting point for technology adoption is so low.

Exponential growth
The S-curve becomes evident. The absolute amount of growth each year increases, but the growth rate starts to decay.

Exponential growth transitioning into logarithmic growth
Absolute growth increases, and the S-curve reaches its maximum steepness. The growth rate continues to decay.

Logarithmic growth
Growth rates gradually approach zero until the S-curve once again appears flat.

Source: Authors.

cases, data limitations prevented us from evaluating the current level of effort made toward a particular target, and we note this accordingly.

Assessing the gap between recent progress and future action needed to meet 1.5°C-compatible targets requires projecting a trajectory of future change for each indicator. The simplest approach is to assume that growth continues at its current rate of change following a purely linear trajectory, and, indeed, this was an effective method for many indicators. However, it is unlikely that all indicators will follow a linear path. For example, the adoption of new technologies has often followed an S-curve trajectory (Figure 1). At the emergence stage of an S-curve, annual growth rates are high as promising research, development, and demonstration projects are underway, but adoption of the new technology remains quite low. Then, in the breakthrough stage, adoption of the technology bends upward, with sustained exponential growth rates. Once the technology begins to diffuse more widely, the rate of adoption of the technology reaches its steepest slope and exponential growth begins to decay. Finally, as society reconfigures around the new technology, adoption reaches a saturation point and growth rates approach zero. The exact shape of such a curve is highly uncertain, and technologies may encounter obstacles that may alter or limit their growth. But given the right conditions (e.g., supportive policies and investments), adoption of new technologies can reach positive tipping points, after which self-amplifying feedbacks kick in to spur rapid, far-reaching changes that can cascade from one system to another or from one geography to another (Box 1).

It is also important to note that, in addition to technology adoption, social and political forces can also contribute to or hinder nonlinear change (Moore et al. 2022). Our assessment of recent progress made toward near-term targets does not consider these factors fully, given the challenges of modeling these effects and data limitations. However, a body of research is emerging on this topic, and further consideration is warranted in future research.

BOX 1 | Tipping points and self-amplifying feedbacks

The point at which an S-curve reaches the breakthrough stage can also be conceptualized as a tipping point—defined broadly as a critical threshold beyond which a system reorganizes often abruptly or irreversibly (IPCC 2022b). In this context, tipping points generally occur when the cost of a new technology falls below that of the incumbent, such that the value of switching to the new technology is greater than its cost. Factors beyond monetary cost, such as an improvement in the technology or an increase in the value of the technology as more people adopt it, can also push technology adoption past a tipping point. Oftentimes, seemingly small changes in these factors can trigger these disproportionately large responses within systems that catalyze the transition to a different state (Lenton et al. 2008; Lenton 2020).

Crossing tipping points can trigger self-amplifying feedbacks that help accelerate the diffusion of new technologies by pushing down costs, enhancing performance, and increasing social acceptance (Arthur 1989; Lenton 2020; Lenton et al. 2008). Learning by doing in manufacturing, for example, can generate progressive advances that lead to more efficient production processes, while reaching economies of scale can progressively lower unit costs. Similarly, as complementary technologies (e.g., batteries) become increasingly available, they can boost functionality and accelerate uptake of new innovations (e.g., electric vehicles) (Sharpe and Lenton 2021). These gains allow companies that adopt new technologies to expand their market shares, deepen their political influence, and amass the resources needed to petition for more favorable policies. More supportive policies, in turn, can reshape the financial landscape in ways that incentivize investors to channel more capital into these new technologies (Butler-Sloss et al. 2021).[a] Such reinforcing feedbacks, then, can spur adoption and help new innovations supplant existing technologies (Victor et al. 2019).

Widespread adoption of new technologies, in turn, can also have cascading effects, requiring the development of complementary innovations, the construction of supportive infrastructure, the adoption of new policies, and the creation of regulatory institutions. It can also prompt changes in business models, job availability, behaviors, and social norms, thereby creating a new community of people who support (or sometimes oppose) further changes (Victor et al. 2019). Meanwhile, incumbent technologies may become caught in a vicious spiral, as decreases in demand cause overcapacity and lead to lower utilization rates. These lower utilization rates, in turn, can increase unit costs and lead to stranded assets.

Note: [a] While discussed in the context of low-carbon technologies, this self-amplifying feedback loop is not inherently positive. Private sector institutions that expand their market share, deepen their political influence, and amass the resources needed to petition for more supportive policies do not always use their power for the public good. Some may leverage their influence to advance their own interests that are at odds with societal goals (e.g., hampering innovation of other low-carbon technologies, advocating for less restrictive regulations across other environmental harms, petitioning for policies that protect their profit margins). Critically, governments have a role to play in effectively regulating the private sector on behalf of the public and in service to societal goals.

To assess global progress made toward 1.5°C-compatible targets, we first evaluated the likelihood that each indicator will follow an S-curve in the future, placing them into one of three categories based on our understanding of the literature and consultations with experts: "S-curve likely," "S-curve possible," and "S-curve unlikely." We then employed different methods to assess progress made for each class of indicators.

"S-curve unlikely" indicators: Assessment of progress based on linear trendline

We classified more than half of our indicators as "S-curve unlikely." More specifically, we do not expect these indicators to follow the S-curve dynamics seen in technology diffusion, given that they do not directly track technology adoption. These occurred primarily within the sections on Forests and Land, Food and Agriculture, and Finance (e.g., reforestation, reducing food waste, and increasing climate finance).

For those "S-curve unlikely" indicators with sufficient historical data, we calculated a linear trendline based on the most recent 5 years of historical data. For several indicators, most notably those in the forests and land sector, we constructed a linear trendline based on 10 years of historical data to account for natural interannual variability, where possible.[8] We then extended this trendline out to 2030 and compared this projected value to the indicator's target for the same year. Doing so enabled us to assess whether recent progress made toward the target was on track.

Next, we calculated an "acceleration factor" for each indicator with sufficient historical data by dividing the average annual rate of change needed to achieve the indicator's 2030 target[9] by the average annual rate of change derived from the historical 5-year (or 10-year) trendline (Appendix A). These acceleration factors quantify the gap in global action between current efforts and those required to limit global warming to 1.5°C. They indicate whether recent historical rates of change need to increase 2-fold, 5-fold, or 10-fold, for example, to meet 2030 targets (Appendix B).[10] We then used these acceleration factors to assign our indicators one of five categories of progress:

✓ **Right direction, on track.** The historical rate of change is equal to or above the rate of change needed. Indicators with acceleration factors between 0 and 1 fall into this category. However, we do not present these acceleration factors since the indicators are on track.

! **Right direction, off track.** The historical rate of change is heading in the right direction at a promising yet insufficient pace. Extending the historical linear trendline would get the indicators more than halfway to their near-term targets, and so indicators with acceleration factors between 1 and 2 fall into this category.

✕ **Right direction, well off track.** The historical rate of change is heading in the right direction but well below the pace required to achieve the 2030 target. Extending the historical linear trendline would get them less than halfway to their near-term targets, and so indicators with acceleration factors of greater than or equal to 2 fall into this category.[11]

↩ **Wrong direction, U-turn needed.** The historical rate of change is heading in the wrong direction entirely. Indicators with negative acceleration factors fall into this category. However, we do not present these acceleration factors since a reversal in the current trend, rather than an acceleration of recent change, is needed for indicators in this category.

? **Insufficient data.** Limited data make it difficult to estimate the historical rate of change relative to the required action.

"S-curve possible" indicators: Assessment of progress based on linear trendline

We classified another nine indicators as "S-curve possible," which do not fall neatly within either the S-curve likely or the S-curve unlikely classes. These indicators do not track zero- or low-emission technology adoption directly, but adoption of new technologies will likely have some impact on their future trajectories, alongside many other factors, such as increases in resource efficiency. Thus, although these indicators have generally experienced linear change in the past, they could experience some unknown form of rapid, nonlinear change in the coming decades if the nonlinear aspects begin to outweigh the linear ones. For example, reducing carbon intensity in the power sector is dependent on multiple trends: an increase in the efficiency of fossil fuel power, which is linear; switches between higher-emitting and lower-emitting fossil fuel power sources, which are generally nonlinear; and a switch from all types of fossil fuel power to zero-carbon power, which is expected to be nonlinear. If the nonlinear growth in zero-carbon power overtakes the linear growth in efficiency, the trajectory of carbon intensity could follow an inverted S-curve.

For these "S-curve possible" indicators, we followed the same methods as above and used a linear trendline to calculate acceleration factors and categorize progress, as recent historical data for these indicators have been following roughly linear trajectories (Appendix A). However, we noted in our analysis that, should nonlinear change begin, progress could unfold at significantly faster rates than expected, and the gap between the existing rate of change and required action would shrink.

"S-curve likely" indicators: Assessment of progress accounting for nonlinear change

We classified the remaining nine indicators as "S-curve likely," as we considered those that directly track the adoption of specific technologies—or, in some instances, a set of closely related technologies (e.g., solar and wind power)—to be prime candidates for experiencing S-curve dynamics in the future. These technologies are innovative, often displacing incumbent technologies (e.g., renewable energy, electric vehicles, green hydrogen). Critically, categorizing an indicator as "S-curve likely" does not guarantee that it will experience rapid, nonlinear change over the coming years; rather, it signifies that, if and when adoption rates of these technologies begin to increase, such growth will likely follow an S-curve.

Still, for such technologies it is unrealistic to assume that future uptake will follow a linear trajectory (Abramczyk et al. 2017; Mersmann et al. 2014; Trancik 2014); and, consequently, it is inappropriate to rely on acceleration factors to evaluate mitigation efforts. Instead, we based our assessment of progress on multiple lines of evidence, including literature reviews, expert consultations, and fitting S-curves to the historical data where appropriate (Appendix C). In assessing progress, a key step was to identify which of the following stages of adoption applies to each technology:

- **Emergence**. Within this stage, the indicator's current value is less than 5 percent of its saturation level, which we assumed to be the more ambitious bound of the indicator's long-term target. Fitting an S-curve to historical data is highly uncertain in such an early stage (Kucharavy and De Guio 2011; Crozier 2020; Cherp et al. 2021). So, for these indicators, we present an illustrative S-curve extrapolating the current trend, but we defaulted to "well off track" in our assessment of these indicators' recent progress. If we found compelling evidence that a breakthrough is near, we upgraded the indicator to a higher category.
- **Breakthrough**. During this stage of an S-curve, the indicator's current value is between 5 and 50 percent of its saturation level, and an exponential trendline is the best fit for the past five years of data. Exponential growth will likely continue in the near future, and, accordingly, we fit an S-curve to the historical data. We then considered this fitted S-curve as one line of evidence in our assessment of recent progress (Box 2).
- **Diffusion**. Technologies eventually begin to diffuse widely across society, and at this stage, the indicator's current value is between 5 and 80 percent of its saturation level. Its adoption rate is moving upward, and a linear trendline is the best fit for the past five years of data. Future uptake will likely continue on a roughly linear trajectory in the near future before eventually declining. We fit an S-curve to the historical data, and we then considered this fitted S-curve as one line of evidence in our assessment of recent progress (Box 2).

- **Reconfiguration**. In this final stage, the indicator's current value is greater than 50 percent of its saturation level, and a logarithmic trendline is the best fit for the past five years of data. Adoption rates will likely stabilize and growth rates will decline as it approaches the saturation point. We fit an S-curve to the historical data, and we then considered this fitted S-curve as one line of evidence in our assessment of recent progress (Box 2).

We also determined instances in which an indicator is **not following a smooth S-curve**, because none of these criteria were met. Many technologies run into obstacles or barriers, which could prevent them from following a smooth S-curve.

BOX 2 | Methods for fitting an S-curve to historical data

To fit an S-curve to the historical data, we used a standard logistic S-curve function, which is based on three main inputs: the saturation level, which we assumed to be the more ambitious bound of the indicator's long-term target; the maximum growth rate; and the midpoint of the S-curve. We then adjusted the growth rate and the midpoint of the function until the S-curve most closely fit all historical data.

We then compared the S-curve's projected value for 2030 to our near-term target for each indicator. An S-curve extrapolation above the target suggests that the indicator is "on track." An S-curve that gets more than half of the way from the current value to the 2030 target indicates that the indicator is likely to be "off track," and if the extrapolation is less than half of the way from the current value to the 2030 target, the indicator is likely to be "well off track." For the few indicators for which this analysis is appropriate, we present the full results of the S-curve fitting in Appendix C.

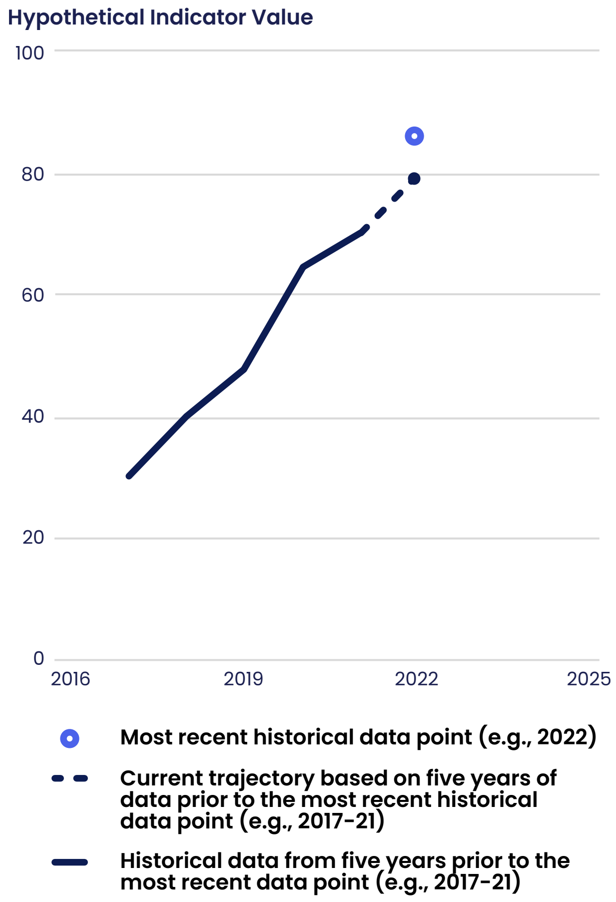
Given the uncertainty of S-curve projections, this curve fitting represents just one line of evidence that we considered, alongside a literature review and consultation with experts. If we found relative consensus among this S-curve fitting exercise, the literature, and consultation with experts, then determining the indicator's category of progress was straightforward. If we found disagreement among these lines of evidence, we had to make a judgment call by identifying the most compelling lines of evidence. We discuss these lines of evidence in this report in Appendix C. More information on our methods for assessing progress can be found in Jaeger et al. (2023), the technical note that accompanies this report.

Analysis of most recent data point

In addition to assessing progress made toward 2030 targets, we also analyzed whether an indicator's most recent data point represents a meaningful improvement or worsening, relative to its historical trendline if sufficient data are available. Essentially, we extended the historical trendline from the previous 5 years of data (or 10 years for forests and land indicators where possible) to project a data point for the most recent year for which we have data (Figure 2). For example, if our most recent data point is 2022, we used data from 2017 to 2021 to construct a historical trendline and then extended that trendline to project a data point for 2022.

We then compared our most recent data point to this projected data point on the extended historical trendline. If the most recent data point, for example, was more than 5 percent higher than the projected value on the extended trendline for an indicator that needs to increase to achieve its 2030 target, we noted that the most recent year of data for this indicator represents an improvement relative to the historical trendline. But if the most recent data point falls more than 5 percent below the projected value on the extended historical trendline for the same indicator, we noted that the most recent year of data for this indicator represents a worsening relative to the historical trendline. Determining the extent to which an improvement or worsening is either temporary or part of a longer-term trend, however, will only be possible in future years.

FIGURE 2 | Methods for comparing most recent year of data to extended historical trendline



Source: Authors.

Selection of recent developments

For each sector, we also highlight recent developments—from adopting new policies to investing in the development of more nascent technologies to disbursing financial pledges—that have occurred primarily since the 26th Conference of the Parties (COP26) in Glasgow. For many of our indicators, it can take time for actions undertaken by governments, civil society,

and the private sector to spur global change. Yet these advances still represent important shifts made in the real-world economy. Accordingly, a more comprehensive snapshot of the state of climate action requires both analysis of progress made toward our sectoral 1.5°C-aligned targets, and a summary of the measures that may support (or hinder) achieving them by 2030.

To identify the recent developments most relevant to each sector, we restricted our search to those that fall into one of the categories of enabling conditions outlined in Boehm et al. (2022)—innovations in technologies, supportive policies, institutional strengthening, leadership, and shifts in behavior and social norms. Note that the significance of enabling conditions differs by sector. In power, for example, many of the technologies needed to decarbonize the sector are mature and commercialized, while in industry or food and agriculture, these innovations remain far more nascent, such that achieving these sectoral targets will likely require considerable investment in research, development, and deployment. Similarly, while many countries have set targets and announced national strategies focused on electrifying transport or conserving ecosystems, far fewer have put in place similar goals or plans to decarbonize buildings or shift consumption patterns. Thus, we hewed closely to the specific enabling conditions outlined for each sector in Boehm et al. (2022) when identifying recent developments. Finally, we focused primarily on developments that are global in scope, though we also included those that are from particularly important geographies (e.g., major emitters, large economies that can shape global trends, countries that contain disproportionate amounts of high-carbon ecosystems, primary producers of an emissions-intensive good, countries that have yet to adopt a particular zero-carbon technology, etc.).

More specifically, we primarily relied on searches of gray literature, newsletters, and policy trackers from leading organizations within these sectors (e.g., the International Energy Agency, International Renewable Energy Agency, C40, World Green Building Council, Mission Possible Partnership, World Steel Association, Bloomberg New Energy Finance, Institute for Transportation and Development Policy, International Transport Forum, International Council on Clean Transportation, New York Declaration on Forests, Food and Agriculture Organization of the United Nations, and Climate Policy Initiative), newspaper articles from major outlets (e.g., Reuters, the Associated Press, the *New York Times, the Guardian*), and nationally determined contributions (NDCs). We restricted our searches to the period from November 2021 to August 2023, though we included some recent developments that predated this period where relevant.

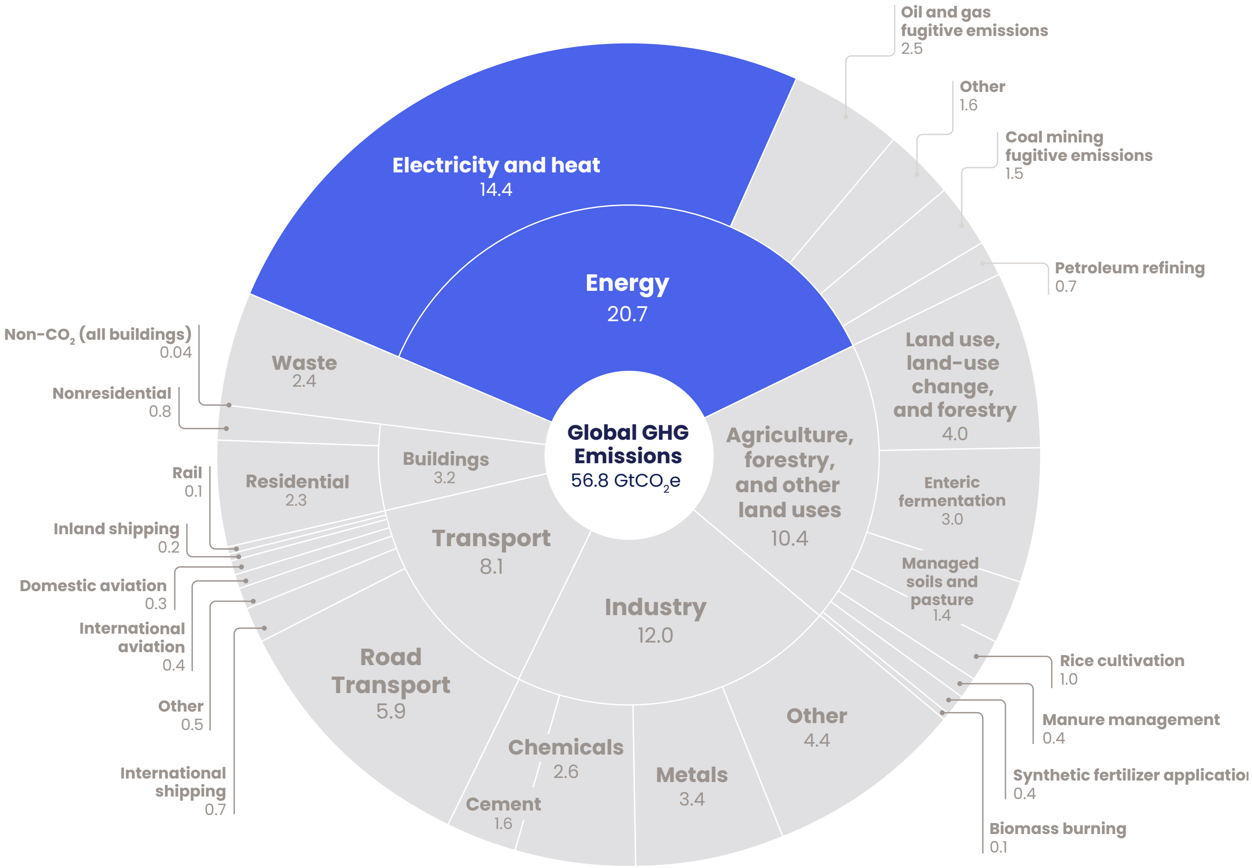
SECTION 2

Power

Around the world, access to affordable and reliable power underpins modern society (UNSD 2023), enabling people to work, cook, learn, take care of each other, and more. Yet nearly 10 percent of the world's population—some 680 million people—do not have access to electricity, with many still using firewood for their most basic energy needs (IEA 2023p). To meet these large gaps in access to electricity and improve living standards, demand for power is rising rapidly (IEA 2022t).

Today's growing power sector is highly emissions-intensive. Because so much electricity comes from burning coal and fossil gas, electricity generation accounted for around 25 percent of global greenhouse gas (GHG) emissions in 2021 (Figure 3) and has long remained the single-largest source of carbon dioxide (CO_2) emissions globally (Figure 4). Indeed, over the last two decades, CO_2 emissions from electricity production have increased by 0.25 gigatonnes (billion metric tons) of carbon dioxide ($GtCO_2$) each year (IEA 2021f, 2022g). And, while these emissions contracted by around 3.5 percent in 2020 due to responses to the COVID-19 pandemic (e.g., reduction of industrial and commercial electricity demand [Bertram et al. 2021]), they rebounded to a record high of about 15 gigatonnes of carbon dioxide equivalent ($GtCO_2e$) in 2022 (IEA 2023o).

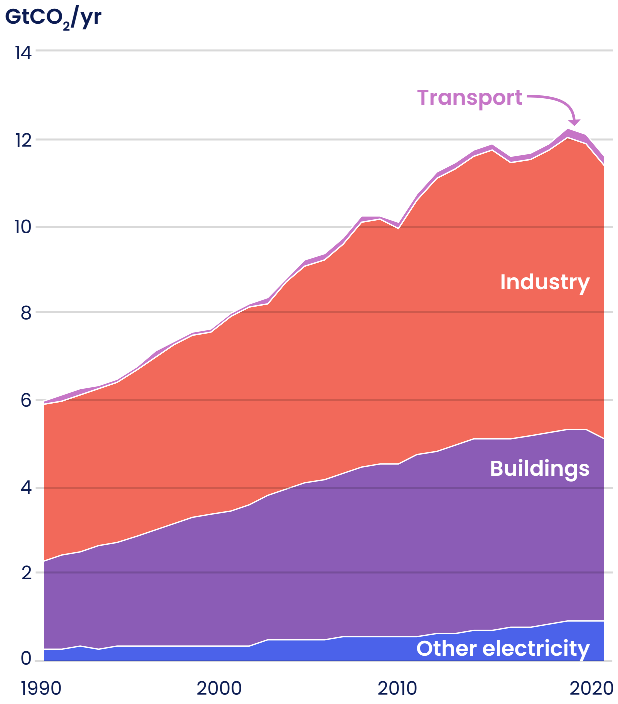
FIGURE 3 | Power's contribution to global net anthropogenic GHG emissions in 2021



Notes: CO_2 = carbon dioxide; GHG = greenhouse gas; $GtCO_2e$ = gigatonnes of carbon dioxide equivalent. Although this figure highlights GHG emissions from electricity and heat, this chapter on power focuses primarily on electricity generation, which accounts for more than 90% of CO_2 emissions from the power sector. The "heat" component of this sector accounts for GHG emissions from the burning of fossil fuels to provide heat to industrial processes, such as steel production.

Sources: Minx et al. (2021); European Commission and JRC (2022).

FIGURE 4 | Global CO_2 emissions from power by end-use sectors



Notes: CO_2 = carbon dioxide; $GtCO_2/yr$ = gigatonnes of carbon dioxide per year. CO_2 emissions presented in this time series are from electricity only and do not cover the heat component of power emissions shown in Figure 3. Also, to disaggregate CO_2 emissions by end-use sectors, we rely on a different data source than Minx et al. (2021) and European Commission and JRC (2022). These disaggregated data are available through 2020 only.

Source: IEA (2023l).

The growing demand for power, and our current reliance on fossil fuels to create it, makes transforming today's global power sector urgent for limiting global temperature rise to 1.5°C. Decarbonizing the power sector is also vital because decarbonization pathways across other major sectors (e.g., buildings, industry, and transport) will be contingent on a decarbonized power sector's ability to provide abundant access to zero-carbon electricity for many end uses.[12]

Fortunately, there are encouraging signs that the structural transformations needed across the global power sector have already begun. Clean power technologies like solar and wind are widely mature, and the cost of renewable energy and storage technologies has continued to plummet at rates unprecedented in the energy sector, leading to record-breaking growth in adoption in 2022 (IRENA 2023b). Solar photovoltaics (PV) and onshore wind are now the cheapest sources of new-build generation for at least two-thirds of the global population (BloombergNEF 2020), and, between 2015 and 2022, solar and wind increased from 5 percent of global electricity generation to 12 percent of global electricity generation (Ember 2023). In 2022, the net growth of wind and solar generation alone (+560 TWh) met 80 percent of all global electricity demand growth (+690 TWh) (Wiatros-Motyka et al. 2023) (see Figure 5). In fact, some experts predict that 2022 represents the peak of total emissions in the power sector (Wiatros-Motyka et al. 2023), positioning the global economy to enter a new era of falling power sector emissions.

FIGURE 5 | Role of zero-carbon versus fossil power sources in meeting rise in electricity demand in 2022

Notes: RES = renewable energy sources; TWh = terawatt hours.

Source: Wiatros-Motyka et al. (2023).

Russia's invasion of Ukraine has pushed the world to a critical juncture in this transformation. As countries seek to secure their energy future in a world without Russian-supplied oil and gas, they face a stark choice between doubling down on fossil fuels or rapidly expanding zero-carbon power. And, while some countries have indeed reopened shuttered fossil fuel infrastructure during this time of crisis, investments in zero-carbon energy technologies (almost all of which produce or use electricity) surpassed $1 trillion in 2022, matching investment in fossil fuels for the first time in history (Wiatros-Motyka et al. 2023). The crisis has also driven new investments in improving energy efficiency, one of the largest untapped resources for decarbonizing the sector (Bond et al. 2023).

Particularly promising signs of this transformation are in the buildup of solar and wind power. Currently, more solar and wind power is in the global pipeline (1,200 GW and 1,800 GW, respectively) than all solar and wind power currently operating (1,000 GW and 900 GW, respectively) (GEM 2023b; IRENA 2023a). While this progress is compelling, it also highlights the slow permitting and construction times in many countries, which often impede and delay construction of planned projects. Streamlining these processes would allow for faster deployment of zero-carbon power solutions. There has additionally been a renewed increase in nuclear power from some countries, with 270 GW in the pipeline, compared to 410 GW currently operating (IEA 2022u; GEM 2023b). Continued investment in these zero-carbon power sources, particularly in light of the Russian-caused energy crisis, will be required for accelerating the transformation to a decarbonized power sector for all.

Global assessment of progress for power

Electricity generation must be decarbonized, primarily through shifting to zero-carbon power and phasing out fossil fuels like coal and gas. Simultaneously, we will need to close gaps in energy access, use energy more efficiently, expand grid capacity, and prioritize energy storage and flexibility.[13] These shifts will be key to ensuring that global warming is limited to 1.5°C.

These changes must occur in a manner that is equitable and sustainable. Historically, a handful of countries in the developed world have been responsible for generating a vast proportion of emissions. These nations will need to lead the way in delivering clean energy transitions by phasing out fossil fuels and demonstrating how to construct large-scale zero-carbon power generation

TABLE 1 | Summary of global progress toward power targets

INDICATOR	MOST RECENT DATA POINT (YEAR)	2030 TARGET	2035 TARGET	2050 TARGET	LIKELIHOOD OF FOLLOWING AN S-CURVE	ACCELERATION FACTOR	STATUS
Share of zero-carbon sources in electricity generation (%)[a]	39 (2022)	88–91	98–99 (2040)	99–100	⤴	N/A; author judgment[b]	!
Share of coal in electricity generation (%)	36 (2022)	4	0–1 (2040)	0	⇉	7x	✗
Share of unabated fossil gas in electricity generation (%)	23 (2022)	5–7	1 (2040)	0	⇉	>10x	✗
Carbon intensity of electricity generation (gCO_2/kWh)	440 (2022)	48–80	2–6 (2040)	<0[c]	⇉	9x	✗

Notes: gCO_2/kWh = grams of carbon dioxide per kilowatt-hour. See Jaeger et al. (2023) for more information on methods for selecting targets, indicators, and datasets, as well as our approach for assessing progress.

[a] Zero-carbon sources include solar, wind, hydropower, geothermal, nuclear, marine, and biomass technologies.

[b] For indicators categorized as S-curve likely, acceleration factors calculated using a linear trendline are not presented, as they would not accurately reflect an S-curve trajectory. The category of progress was determined based on author judgment, using multiple lines of evidence. See Appendix C and Jaeger et al. (2023) for more information.

[c] Achieving below zero–carbon intensity implies biomass power generation with carbon capture and storage. These targets limit bioenergy with carbon capture and storage use to 5 $GtCO_2$ per year in 2050. See Jaeger et al. (2023) for more information about the sustainability criteria used in target-setting.

Sources: Historical data from Ember (2023); targets from CAT (2023a).

capability domestically,[14] while simultaneously helping developing countries to decarbonize their power sectors and offering new economic development opportunities.

This section examines the progress of the global power transition by analyzing four indicators related to electricity generation: share of zero-carbon sources in electricity generation; share of coal in electricity generation; share of unabated fossil gas in electricity generation; and carbon intensity of electricity generation (Table 1). All indicators show that change is headed in the right direction, but at an insufficient rate.

Shift to zero-carbon power

Scaling up zero-carbon power technologies will help decarbonize the power sector (IPCC 2022b). These technologies, which generate little to no CO_2 during their operational cycles, include solar, wind, hydropower, biomass, nuclear, geothermal, and marine technologies.[15] By providing zero-carbon power, such technologies can help meet global energy needs without increasing GHG emissions and local air pollutants. Out of all zero-carbon power sources, hydropower contributed the largest share of global electricity generation, at 15 percent (4,300 TWh) in 2022 (Ember 2023). Nuclear power output, despite having plateaued since 2006 (WNA 2022), maintains its place as the second-largest zero-carbon contributor to total generation at around 9 percent (2,600 TWh). Solar and wind are the fastest-growing sources of electricity generation (IRENA 2022a; IEA 2023n) and together accounted for 12 percent of total generation (3,400 TWh) in 2022. Meanwhile, all other zero-carbon sources, including bioenergy, accounted for 3 percent of total generation (780 TWh) in 2022 (Ember 2023). It is important to note that more than 90 percent of investment in zero-carbon energy has occurred in advanced economies and China (IEA 2023m). As growth of these power sources continues, it will be important to ensure more even investments in zero-carbon energy; indeed, mobilizing greater financing for emerging and developing economies is critical to avoid clean energy imbalances between developed and developing countries.

Despite fast and continued growth in zero-carbon power technology deployment, the *share* of zero-carbon power sources in electricity generation showed only slow growth between 2000 (36 percent) and 2022 (39 percent) (Figure 6). This is because the growth in zero-carbon power has proceeded in line with total power generation due to increased electrification and improved energy access. Accordingly, to clearly track the shift to zero-carbon power that is required for keeping 1.5°C in sight, we track the *share* of zero-carbon sources in total global electricity generation, rather than growth of technology deployment alone.

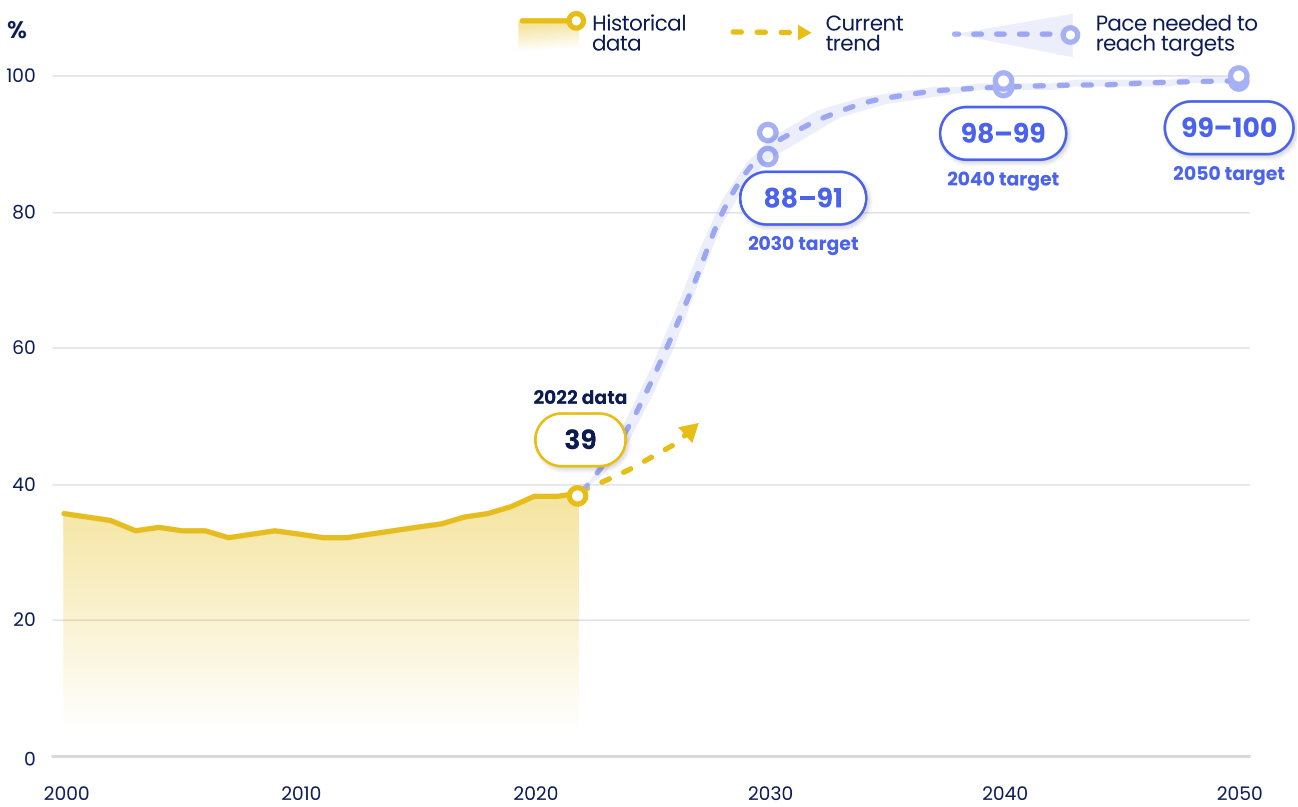
POWER INDICATOR 1:
Share of zero-carbon sources in electricity generation (%)

- **Targets:** The share of zero-carbon sources in electricity generation reaches 88–91 percent by 2030, 98–99 percent by 2040, and 99–100 percent by 2050.

The share of zero-carbon sources in global electricity grew slightly in 2022 to reach 39 percent, a continuation of recent trends. However, the world needs to increase the share of zero-carbon sources in global electricity to 88–91 percent by 2030 (a target that helps align the power sector with 1.5°C-compatible pathways). Different zero-carbon technologies are on different trajectories. Solar power is in the breakthrough stage of an S-curve, growing exponentially over the past five years, while wind power is in the diffusion stage of an S-curve, having grown exponentially in the past but growing linearly over the last five years (see Box 3). Nuclear power, hydropower, and other zero-carbon power sources like bioenergy have been changing linearly (or plateauing in the case of nuclear). If the trajectories of each of these technologies are extrapolated, the share of zero-carbon power sources in electricity generation is making promising progress, but, though heading in the right direction, recent rates of change remain off track.

FIGURE 6 | Historical progress toward 2030, 2040, and 2050 targets for share of zero-carbon sources in electricity generation

Right Direction, Off Track **S-Curve Likely**



Note: Zero-carbon sources include solar, wind, hydropower, geothermal, nuclear, marine, and biomass technologies. For indicators categorized as S-curve likely, acceleration factors calculated using a linear trendline are not presented, as they would not accurately reflect an S-curve trajectory. This current trend arrow is extrapolated based on an S-curve trendline for solar and for wind and a linear trendline for the other technologies. The category of progress was determined based on author judgment, using multiple lines of evidence. See Appendix C and Jaeger et al. (2023) for more information on methods for selecting targets, indicators, and datasets, as well as our approach for assessing progress.

Sources: Historical data from Ember (2023); targets from CAT (2023a).

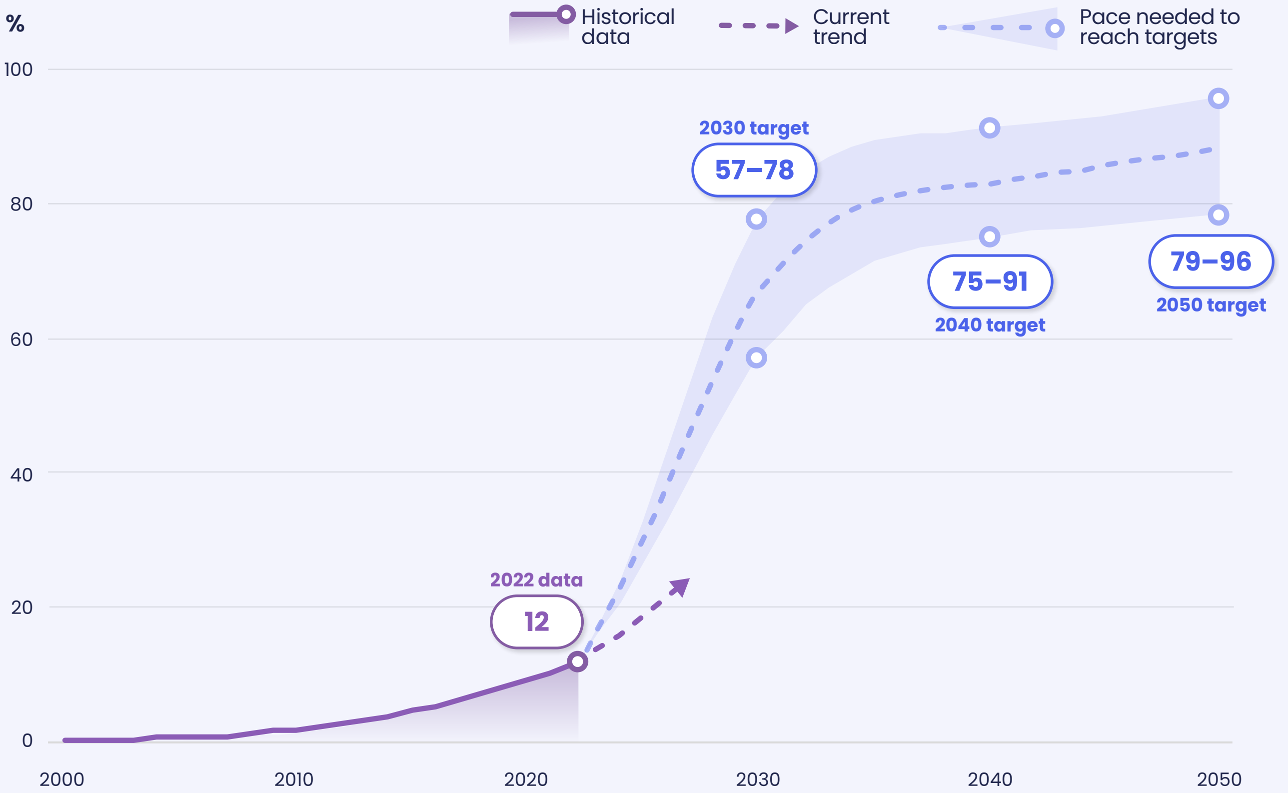
BOX 3 | Share of wind and solar sources in electricity generation

Solar and wind power have been the main contributors to growth in the overall share of zero-carbon sources in electricity generation in recent years. Hydropower and nuclear have traditionally been the largest sources of zero-carbon electricity, but they have been slowly declining in recent years (Ember 2023). Costs of solar and wind have been falling, with additional deployment spurring additional cost declines.

To achieve targets for zero-carbon power aligned with trajectories that limit warming to 1.5°C, the share of wind and solar sources in electricity generation will need to reach 57–78 percent by 2030, and 79–96 percent by 2050.[a] These targets are calculated using methods from CAT (2023a), which are described further in this report's accompanying technical note (Jaeger et al. 2023).

The share of electricity produced from solar and wind has been growing 14 percent per year on average for the past five years, an impressive rate of growth. However, it would have to increase by 24 percent per year in the future to meet the 2030 target, requiring continued acceleration through this decade (Figure B3.1).

FIGURE B3.1 | Historical progress toward 2030, 2040, and 2050 targets for share of wind and solar sources in electricity generation



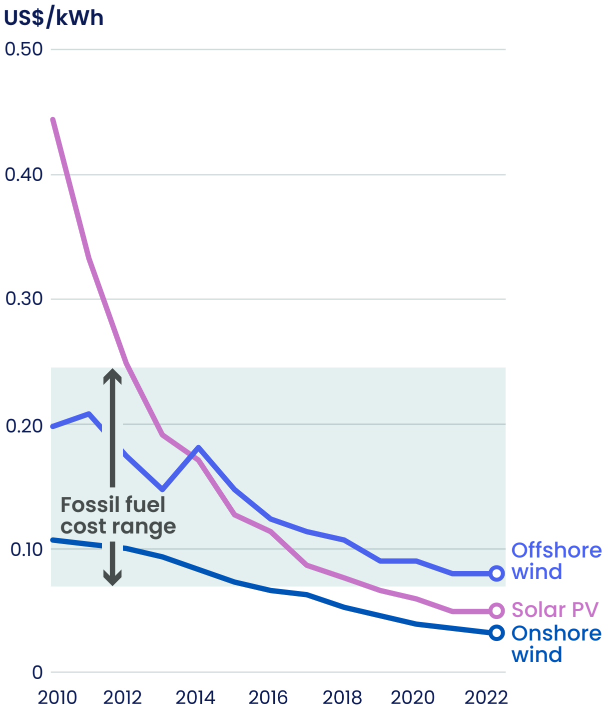
Note: The current trend arrow is extrapolated based on an S-curve trendline for each technology.
Sources: Historical data from Ember (2023); targets from CAT (2023a).

Note: [a] Other analysis from RMI finds that if solar and wind follow a fast S-curve, they would reach 33 percent of electricity generation in 2030; if they follow pure exponential growth, they would reach 39 percent of electricity generation in 2030 (Bond et al. 2023). This is within striking distance of the IEA's Net Zero Emissions (NZE) Scenario (IEA 2022t), which shows a 41 percent share of solar and wind in electricity generation by 2030, but well below this report's target of 53–78 percent in 2030. The scenarios and literature that underpin this report's targets show a higher share of total zero-carbon power and a higher share of wind and solar within zero-carbon power than the IEA's NZE. This is because the IEA NZE shows strong growth in nuclear, fossil gas with carbon capture and storage, biomass, and hydropower generation. Additionally, the NZE has a higher overall carbon intensity of power generation than the average 1.5°C-compatible scenarios used in this report, which means that other sectors decarbonize faster in the NZE.

Many bright spots invite optimism about real progress toward the 2030 target for share of zero-carbon power in electricity generation. Between 2019 and 2022, power generation from zero-carbon technologies grew significantly: most notably solar by 600 TWh (+86 percent) and wind by 680 TWh (+48 percent) (Ember 2023). In recent years, several countries have scaled up wind and solar power at rapid rates (for more information about national-level progress, see Box 4). Indeed, solar manufacturing throughput (the amount that gets produced by manufacturing plants) for solar PV modules grew from 190 GW in 2021 to 260 GW in 2022, the latter representing about 40 percent of total manufacturing capacity (IEA 2023i). Between now and 2030, new announced capacity implies an additional 1.1 TW of throughput in 2030 if it is all ultimately built.

Meanwhile, the costs of these technologies have continued to plummet beyond expectations. Over the past decade, costs have plunged 80 percent for solar, 54 percent for offshore wind, and 65 percent for onshore wind (Figure 7). The price of battery storage—a technology that enables variable renewables—has also fallen substantially, by around 89 percent between 2010 and 2021 (BloombergNEF 2022a).[16] It is important to note here, however, that supply-chain issues for select zero-carbon power technologies (e.g., battery supply shortages caused by lithium shortages) can slow growth.

FIGURE 7 | **Weighted average levelized cost of electricity for selected renewable energy technologies and fossil fuel comparison**



Notes: $/kWh = dollars per kilowatt-hour; PV = photovoltaics.
Source: IRENA (2023b).

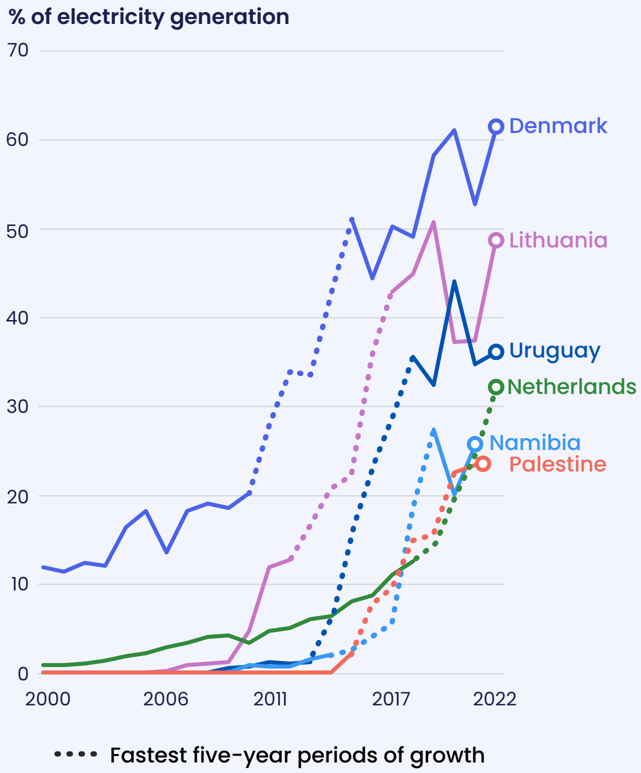
BOX 4 | Where are the most rapid rates of change?

Wind and solar power have emerged as primary drivers of the transition to renewable energy, offering clean, abundant, and cost-effective renewable power with smaller environmental drawbacks than those associated with biomass or hydropower. While many countries are investing in renewable energy, the pace of this transition varies widely. A closer look at countries leading the charge reveals how they are progressing along their transitions and what lessons other countries can learn and apply. Figure B4.1 lists countries that have scaled up solar and wind's share of total power generation the fastest. The jurisdictions are quite geographically varied and demonstrate that a quick scale-up is possible in most regions of the world.

These jurisdictions have relied on a variety of policies and regulations to achieve their success. For example, Denmark, which mostly depends on wind power, achieved its rapid growth ahead of most other countries. From 1999, its government introduced a feed-in tariff, a guaranteed payment for surplus renewable electricity that homeowners and other generators produce. The government also provided use replacement certificates to encourage upgrades for wind turbines (Cook and Lin Lawell 2020). Because Denmark was investing in renewables in a time period before costs had fallen substantially, bottom-up models show that Denmark's rapid shift to more wind and solar power generation stemmed directly from these policy changes, rather than from technological advances (Cook and Lin Lawell 2020). Uruguay has had similar success with feed-in tariffs, and also implemented a reverse-auction system to encourage wind power investment (Westphal and Thwaites 2016).[a] However, it is imperative to ensure that feed-in tariffs decrease as the cost of the technologies drop, to avoid overspending.

BOX 4 | Where are the most rapid rates of change? (continued)

FIGURE B4.1 | The fastest five-year periods of growth of solar and wind as a share of total electricity generation



Source: Jaeger (2023).

Namibia has built up an impressive share of solar power by enacting long-term infrastructure and economic plans, such as direct investment in solar plants (World Economic Forum 2021; Namibia Ministry of Mines and Energy 2017). It also opened up the electricity market in 2015 to allow nonstate parties to purchase electricity directly from independent power producers, encouraging private foreign investment in both end use and generation (GIZ 2022). This policy is intended to help the country switch from being a net energy importer to a net exporter. El Salvador is also hoping to switch from imported fossil fuels to home-grown renewables (IRENA 2022b), building on a long-term 2010–24 energy sector plan, which incentivizes renewable energy projects. Inducements include income tax exemptions for the first 5–10 years of a project's life and duty-free imports on electricity generation equipment (IRENA 2020). In Palestine, the increase in solar PV energy has come from a need for energy self-sufficiency; electricity is imported from Israel and is heavily controlled (Khatib et al. 2021). Small-scale PV allows households and businesses to use the electricity they generate directly and decreases reliance on grid-supplied power. Palestine has also introduced incentives in the form of reduced income taxes for utility-scale PV, which are set to increase with time (Khatib et al. 2021).

As well as building up wind and solar capacity, improving grid infrastructure and efficiency is required to make best use of variable renewables. Many of these jurisdictions have followed up their buildup of wind and solar with large investments in grid infrastructure and expansion; for instance, Uruguay has invested US$1 billion, while Denmark has invested just over €1,30 million (EuropaWire PR 2023; Uruguay XXI 2022). It is also important to note that as some countries have scaled up renewable energy, they have had to rely on importing energy during some periods of low generation, and been able to export it at other times. Therefore, grid interconnectivity is highly important as renewables continue to scale up.

While the above jurisdictions have the highest rates of solar and wind scale-up as a share of total power generation, credit should also be given to countries installing the largest total amounts of wind and solar, including China, the United States, Germany, and India (together making up 54 percent of global power sector generation). The large capacities installed by these countries also help to drive down prices worldwide as the technology continues to scale.

Note: [a] In a reverse-auction system, sellers or developers bid for prices at which they can sell their goods or services, as opposed to a regular auction where buyers bid at increasing costs for a sold good or service (Chen 2022).

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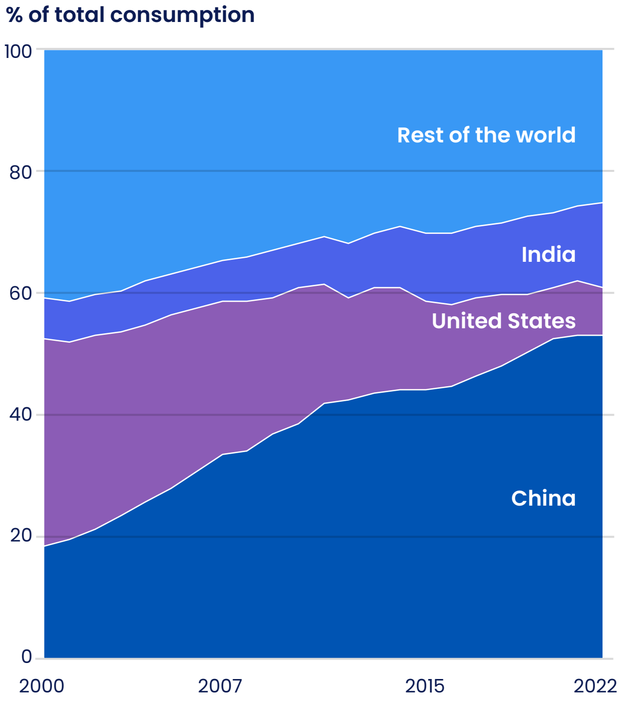
Phase out fossil fuel use in power generation

Across the world, coal is currently responsible for almost 70 percent of total power sector CO_2 emissions, and gas makes up around 25 percent (Ember 2023). Phasing out these power sources, then, will directly decrease overall power sector emissions and emissions intensity, and is crucial for limiting global temperature rise to 1.5°C.

Emissions from both coal and gas are scattered around the world, though most are concentrated in several large economies. China was responsible for around 53 percent of coal usage in 2022, with India (14 percent) and the United States (8 percent) being the second- and third-biggest users, respectively (Figure 8) (Ember 2023). Although the share of coal as a power source has been edging downward in China, total coal usage for power has been steadily rising. Coal usage in India has also increased substantially in the last decade (BP 2022). Although emissions from burning fossil gas dropped slightly in 2020 due to the COVID-19 pandemic, they rebounded in 2021 (IEA 2022t). Fossil gas usage for power generation is largest in the United States, which burns 26 percent of the world's gas used for power generation, followed by the European Union (20 percent), and Russia (8 percent), although gas usage has increased steadily in all regions except Europe since 2011 (Ember 2023). Fossil gas usage is predicted to continue growing strongly in the near future under current policies, especially in emerging economies (BloombergNEF 2022c).

FIGURE 8 | Share of global coal consumption for power generation in China, United States, India, and the rest of the world



Source: Ember (2023).

In addition to their climate impacts, fine particulate matter (PM2.5) and other pollutants, such as sulfur dioxide and nitrogen oxides, emitted by fossil fuel–fired power plants (particularly coal) also have a direct impact on community health. Such pollutants can exacerbate respiratory conditions such as asthma and increase the risk of heart disease and lung cancer (U.S. EPA 2011). Coal-fired power plants, in particular, also generate large amounts of wastewater, which can contain heavy metals, toxic chemicals, and other pollutants and contaminate local water sources, damage aquatic ecosystems, and harm human health. Communities living near fossil fuel–fired power plants are often socioeconomically disadvantaged (Kopas et al. 2020), which further exacerbates vulnerability to these health risks. Addressing the health impacts of fossil fuel–fired power plants and protecting public health thus requires urgent action to regulate and phase out these energy sources.

POWER INDICATOR 2:

Share of coal in electricity generation (%)

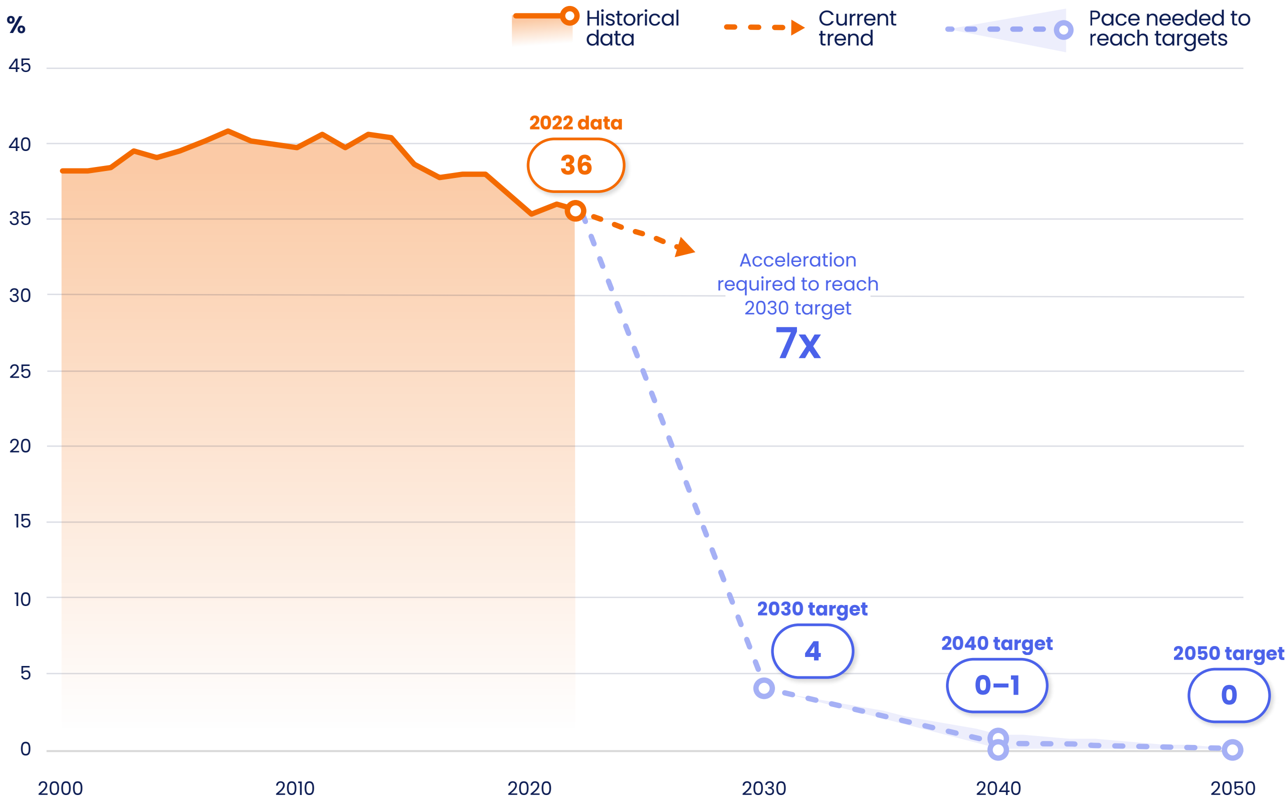
Targets: The share of coal in electricity generation falls to 4 percent by 2030, 0–1 percent by 2040, and then to 0 percent by 2050.[17]

The percentage of power generated from coal increased until 2007. It then slowly began declining, falling by 4 percent during the COVID-19 pandemic, but then rebounded by 3 percent in 2021 before marginally decreasing in 2022 in continuation of recent trends (BP 2022; Ember 2023). While recent rates of change have thus been heading in the right direction, progress still falls short of the 2030 target (Figure 9), and the indicator is well off track. To reduce the share of coal in electricity generation to 4 percent by 2030, the recent speed of decline must accelerate by seven times. However, with the rapid buildup of renewables and their decreasing costs, it is possible that the share of coal in power generation could decrease rapidly and nonlinearly.

Wealthier countries that have historically generated the most emissions and have the greatest capacity to cut them sharply need to demonstrate to the rest of the world how to phase out coal-fired power, including by phasing out fossil fuel subsidies. These countries also bear a responsibility to mobilize significantly more climate finance to support other countries' transitions and to reduce misaligned finance flows (e.g., financing for fossil fuel projects abroad and fossil fuel subsidies). However, clean energy finance from developed countries to developing countries was lower in 2021 than in

FIGURE 9 | Historical progress toward 2030, 2040, and 2050 targets for share of coal in electricity generation

☒ **Right Direction, Well Off Track** **S-Curve Possible**



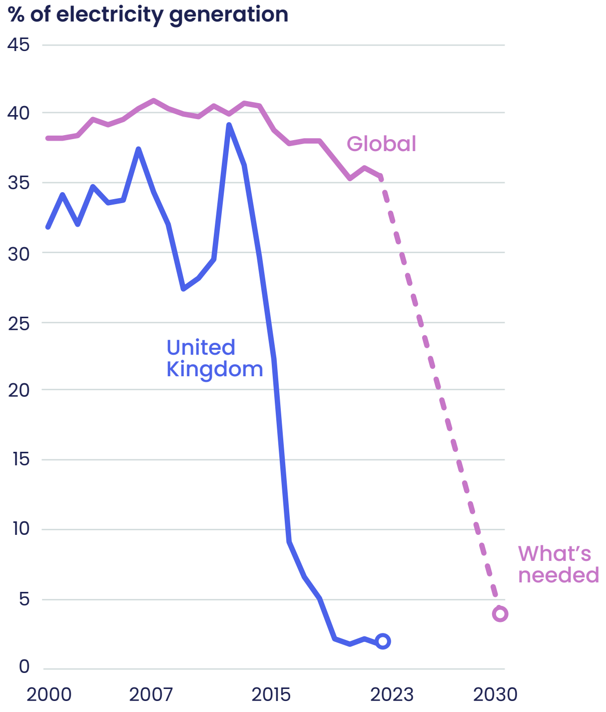
Notes: See Jaeger et al. (2023) for more information on methods for selecting targets, indicators, and datasets, as well as our approach for assessing progress.

Sources: Historical data from Ember (2023); targets from CAT (2023a).

2010 ($10.8 billion in 2021 compared to $12 billion in 2010 (IEA 2023p). In 2022, the G7 ministers of climate, energy, and the environment agreed to end government financing for international coal-fired power generation (G7 Germany 2022). But this promise does not affect the type of power generation that countries finance domestically. Commitments must simultaneously be made to phase out domestic coal and gas use. Indeed, around $1 trillion is still being invested annually in fossil fuel exploration, extraction, and transport (Lazarus and Van Asselt 2018), with the majority of investments coming from developed countries.

As coal power is phased out, it is important to retrain or compensate coal plant workers and to increase the resilience of local communities' economic activities to ensure a just transition (Box 5). Retraining programs can help these workers acquire new skills, find new quality employment, and contribute to the development of a sustainable energy future, while compensation can also be offered to workers affected by the transition. There are many examples of this in practice; Slovakia has provided education, retraining, and coaching to coal industry workers in the Upper Nitra region, while former coal mines such as Anselm in Czechia have been converted into museums that draw tourists, preserving the town's character and economic development (Szőke 2022). Currently, about 8.4 million people worldwide work in the coal value chain, a figure expected to drop to about 6.1 million by 2030 (IEA 2022x). However, renewable energy jobs hit around 13 million in 2022, and are expected to grow further (IRENA 2022c), demonstrating opportunities to retrain traditionally coal-focused workforces.

FIGURE 10 | Share of coal in electricity generation for the United Kingdom and the world



Sources: Historical data from Ember (2023); targets from CAT (2023a).

Fortunately, recent encouraging signs of progress invite optimism that change is possible. India, for example, has announced plans to halt new coal plant construction for five years from 2024, with many other South Asian countries following suit and announcing coal phase-out dates or moratoriums (Abrasu 2023). Meanwhile, the United Kingdom reduced its share of coal for electricity generation from a high of about 40 percent in 2012 to just 2 percent in 2021 (Ember 2023), the fastest fall of any country (Figure 10). Denmark, the Netherlands, and Greece have also achieved reductions in coal use at speeds almost as fast as the United Kingdom (Wiatros-Motyka et al. 2023). From now to 2030, the rest of the world needs to phase down coal electricity generation nearly as fast.

POWER INDICATOR 3:
Share of unabated fossil gas in electricity generation (%)

- **Targets:** The share of unabated fossil gas in electricity generation falls to 5–7 percent by 2030, 1 percent by 2040, and then to 0 percent by 2050.

The share of fossil gas grew from 18 to just over 23 percent of total electricity generation from 2000 to 2019 (Ember 2023). However, it has slightly decreased each year since then, including a decrease in 2022 to reach 23 percent. Unabated fossil gas's share must be brought down to 5–7 percent by 2030 to align with 1.5°C-compatible pathways, which requires an acceleration more than 10 times faster than the current slightly decreasing linear trend (Figure 11).[18] But with the rapid buildup of renewables, the share of fossil gas in power generation could decrease rapidly and nonlinearly.

BOX 5 | **Defining a just transition**

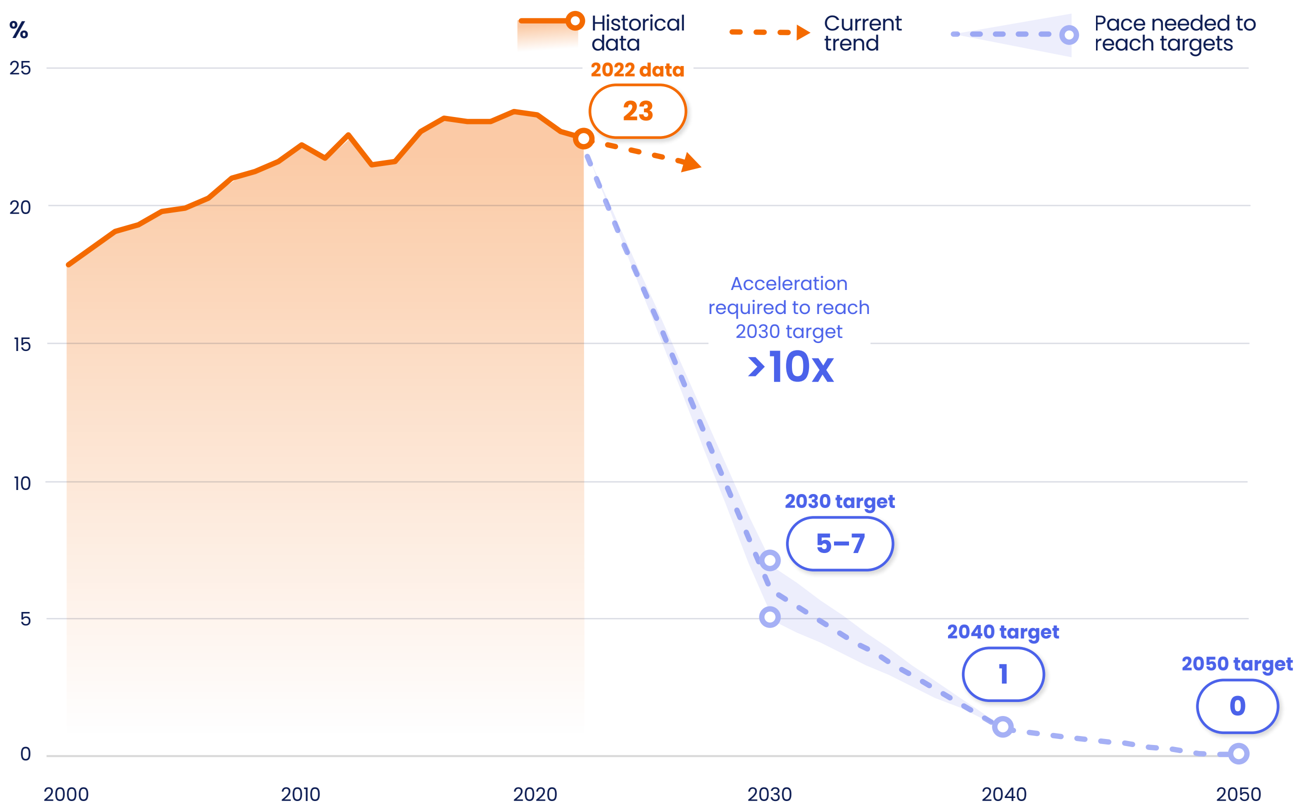
At its core, a just transition elevates concerns about social justice in the transition to net-zero GHG emissions in pursuit of a sustainable economy and society. Although countries and regions conceptualize their own visions and definitions, at its broadest level, a just transition aims to ensure that impacted groups (oftentimes with limited resources) are protected and empowered, social and economic opportunities are maximized, and any challenges are minimized and managed (ILO n.d.). The International Trade Union Confederation (ITUC) defines the just transition as an economy-wide process that produces the plans, policies, and investments that lead to a future where all jobs are green and decent, GHG emissions are at net zero, poverty is eradicated, and communities are thriving and resilient. The ITUC presents a just transition as being informed by social dialogue between workers and their unions, employers, and often governments (ITUC 2017). The Sharm el-Sheikh Implementation Plan (UNFCCC 2022a) reiterates "that sustainable and just solutions to the climate crisis must be founded on meaningful and effective social dialogue and participation of all stakeholders."

Note: GHG = greenhouse gas.

To phase out fossil gas power at the needed pace,[19] zero-carbon energy sources need to be built up quickly, while the construction of new fossil gas power plants needs to be halted. Currently, over 73 percent of power generation from fossil gas is from the developed world. This rapid reduction in fossil gas power generation should then be driven particularly by phasing out fossil gas in developed countries. As with the coal phase-out, gas plant workers should be retrained or compensated to make sure the energy transition is fair and just (see Box 5).

FIGURE 11 | Historical progress toward 2030, 2040, and 2050 targets for share of unabated fossil gas in electricity generation

☒ **Right Direction, Well Off Track** **S-Curve Possible**



Note: See Jaeger et al. (2023) for more information on methods for selecting targets, indicators, and datasets, as well as our approach for assessing progress.
Sources: Historical data from Ember (2023); targets from CAT (2023a).

Decarbonize electricity generation

The carbon intensity of global power generation provides an overall measure of progress on decarbonization of the sector by describing the emissions per unit of electricity generated, unaffected by changes such as added capacity or varying demand.[20] In order to reduce the carbon intensity of electricity generation, top priorities should be the phase-out of coal and gas power generation and the simultaneous buildup of zero-carbon power, particularly solar and wind, all of which are tracked by the prior indicators. Simultaneously, energy will need to be used more efficiently and energy storage solutions scaled up, particularly as the demand for electricity increases as a result of increasing electrification in other sectors.

POWER INDICATOR 4:

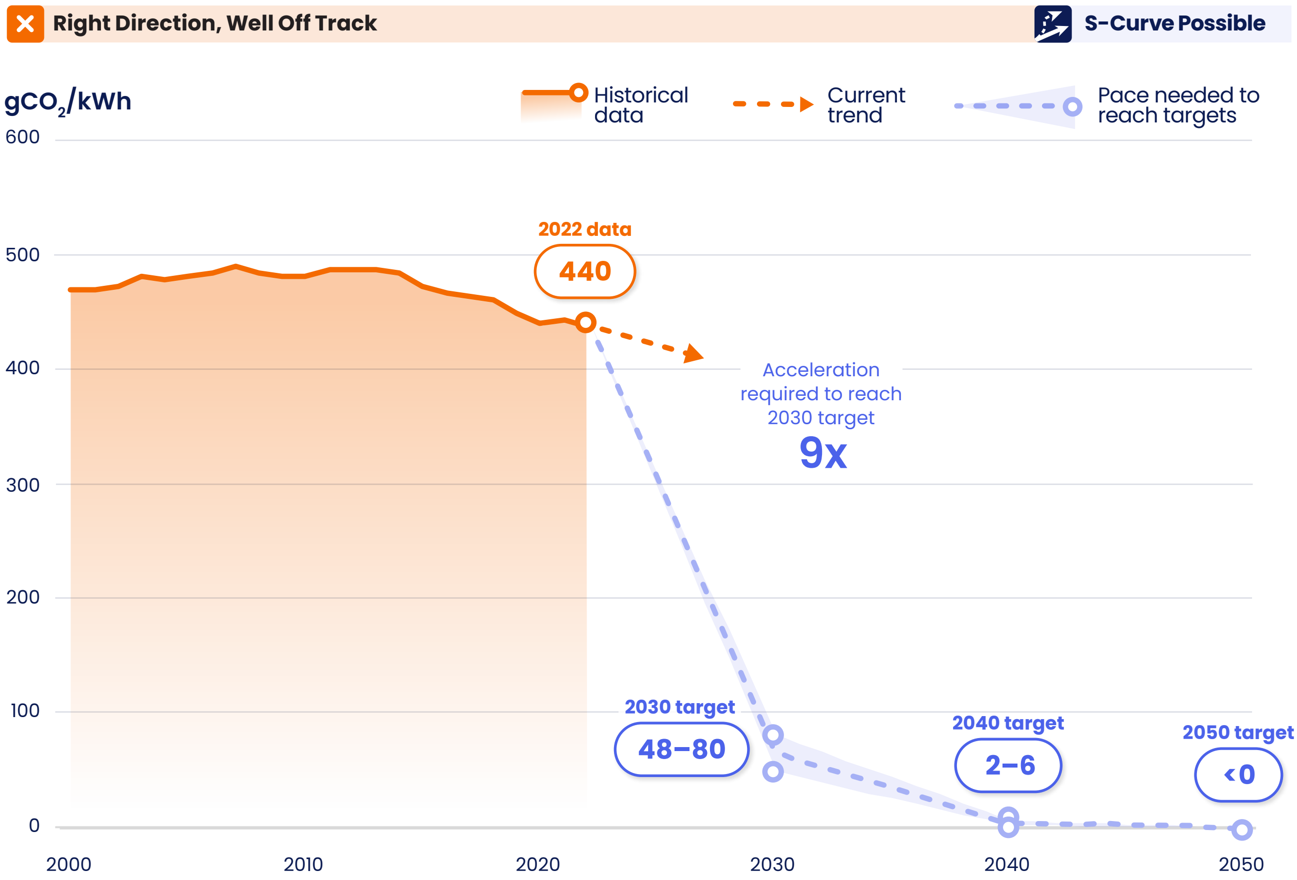
Carbon intensity of electricity generation (gCO_2/kWh)

- **Targets:** The carbon intensity of electricity generation globally falls to 48–80 grams of carbon dioxide per kilowatt-hour (gCO_2/kWh) by 2030, 2–6 gCO_2/kWh by 2040, and then to below zero by 2050.

From 2000 to 2010, the carbon intensity of global power generation gradually increased from 470 gCO$_2$/kWh to 480 gCO$_2$/kWh. Although it has started to decrease slightly since then, reaching 440 gCO$_2$/kWh in 2022, recent trends have roughly continued. The recent rate of decrease needs to be roughly nine times as fast if the 2030 target (48–80 gCO$_2$/kWh) is to be met. Recent rates of change are thus well off track (Figure 12). However, it is possible that progress on this indicator could decrease nonlinearly as zero-carbon power sources drop even further in cost and continue to gain momentum.

Some countries have achieved significant reductions in carbon intensity of electricity generation. One example is Uruguay, which produces over 80 percent of its electricity from renewable sources (Ember 2023), increasing the share of wind generation in the national grid from 1 percent in 2013 to 33 percent by 2022 (Ember 2023; ITA 2022). The country's success can be attributed to several factors, including strong political commitment, a supportive framework of laws and regulations, and favorable conditions for renewables, including regulatory reforms such as a competitive reverse-auction system for large-scale development, a feed-in tariff for small-scale projects,[21] and increased job training and university courses in renewable energy (Westphal and Thwaites 2016; Elliott et al. 2023). Having hydropower reserves also helped Uruguay to meet electricity demand during periods of low wind power as fossil fuels were phased out. These measures have resulted in a 32 percent reduction in Uruguay's electricity price from 2010 to 2021 (CEIC Data n.d.). While Uruguay is a relatively small country, its success and how it was achieved could be replicated in other countries with similar renewable energy potential.

FIGURE 12 | Historical progress toward 2030, 2040, and 2050 targets for carbon intensity of electricity generation



Notes: gCO$_2$/kWh = grams of carbon dioxide per kilowatt-hour. Achieving below zero-carbon intensity implies biomass power generation with carbon capture and storage. These targets limit bioenergy with carbon capture and storage use to 5 GtCO$_2$ per year in 2050. See Jaeger et al. (2023) for more information on methods for selecting targets (including our sustainability criteria), indicators, and datasets, as well as our approach for assessing progress.

Sources: Historical data from Ember (2023); targets from CAT (2023a).

The last several years have also seen important developments in energy storage, where advances are required to continue to lower the carbon intensity of electricity generation. The cost of lithium-ion batteries needed for storage has plummeted in recent years (BloombergNEF 2022a), as described above. Meanwhile, China and the United States are leading the installation of pumped hydropower storage solutions (IEA 2022y, 2022v),[22] and a number of other countries are implementing targets, research and development (R&D) support, and regulatory reforms for energy storage. Spain is aiming for 20 GW of energy storage by 2030, and Germany is incentivizing the combination of renewables and storage (IEA 2022v). These installations and targets have driven global investments in battery storage to grow by an average of 67 percent per year since 2019, reaching $37 billion in 2023 (IEA 2023m). Meanwhile, between 2019 and 2021, more than 8,000 patent applications for energy storage technologies were submitted across the globe—an eightfold increase from 2000 and a promising signal of innovation in the sector (IEA 2022w). Despite these encouraging advances, only 16 GW of storage are currently deployed on grids around the world (IEA 2022v). Model results from the IEA suggest that an over 10,000 percent increase in battery storage capacity is needed by midcentury (IEA 2021b). Additionally, to allow the grid to handle large loads of variable renewables, most countries will have to significantly expand transmission and distribution, as well as demand-response programs.

Recent developments across power

Across the global power sector, this past year has witnessed many developments aimed at boosting zero-carbon power generation and phasing out fossil fuels to ultimately drive decarbonization of electricity generation. A major example is the 2022 Inflation Reduction Act, the largest investment in climate and energy in U.S. history (U.S. DOE 2022b). It authorizes over $390 billion in support for projects that avoid GHG emissions, such as construction of zero-carbon power or energy storage systems. The announcement of this policy has had dramatic knock-on effects, with other countries feeling pressure to match U.S. incentives or risk losing green investments to the United States (European Investment Bank 2023). In February 2023, the European Union announced its unofficial answer to the Inflation Reduction Act, the "Green Deal Industrial Plan," which aims to reduce red tape and increase trade and funding for sustainable technologies such as wind, solar, hydrogen, and energy storage. China is also massively increasing its green investments, spending nearly $550 billion in 2022 on low-carbon technologies, more than all other countries combined (Schonhardt 2023). Additionally, India has allocated more than $8 billion for clean energy in 2023–24 (CAT 2023b). Though these bright spots are significant, more concerted action is needed to meet targets for zero-carbon power uptake.

At the same time, approximately 560 GW of new coal-fired power stations are in the pipeline, with most planned in developing countries like China, Indonesia, and Bangladesh (GEM 2023a; 2023b). Policymakers in these regions must prioritize development of zero-carbon power over new fossil fuel power plants, halting approvals for new construction. Appropriate funding should be supplied from developed countries to support this transition. Fortunately, recent encouraging signs suggest that trends may be shifting.

Russia's invasion of Ukraine has greatly impacted gas markets, particularly in Europe, which now relies more heavily on gas imports from the United States and Middle East, but also globally as rich countries buy gas reserves that otherwise would have been purchased at a lower price by countries such as Pakistan, India, and Brazil (Ahmed 2022). This has caused these countries to switch to burning more coal for power generation (BP 2022), which leads to even worse health and climate impacts than gas. It has also contributed to power rationing and outages due to uncertainty and fluctuations in coal supply (Singh 2022). It is important to note that if access to natural gas is limited due to higher prices, coal might be perceived as a more accessible option to meet energy needs in countries grappling with energy access challenges. Safeguards must be built to prevent this and encourage countries to meet access gaps by scaling zero-carbon alternatives.

As zero-carbon power is scaled up and fossil fuel usage is phased out, innovative coalitions established over the last year will be critical for driving continued declines in the carbon intensity of power generation. In 2022, the United Nations established the Energy Compact Action Network to match governments seeking support for reaching their clean energy goals with governments and businesses that have pledged to offer financing of over $600 billion by the end of the decade, along with information and capacity sharing (United Nations 2022). Later in the year, at COP27, the Egyptian Presidency launched the Africa Just and Affordable Energy Transition Initiative, which aims to provide at least 300 million people with more access to affordable energy technologies and increase Africa's renewable electricity generation. In 2022, too, philanthropic funders and the U.S. government partnered to launch the Energy Transition Accelerator to mobilize private capital for clean energy transitions in developing countries (McGinn et al. 2022). Meanwhile, the Asian Clean Energy Coalition was launched to mobilize private investment and support for stronger renewable energy policies in Asia.

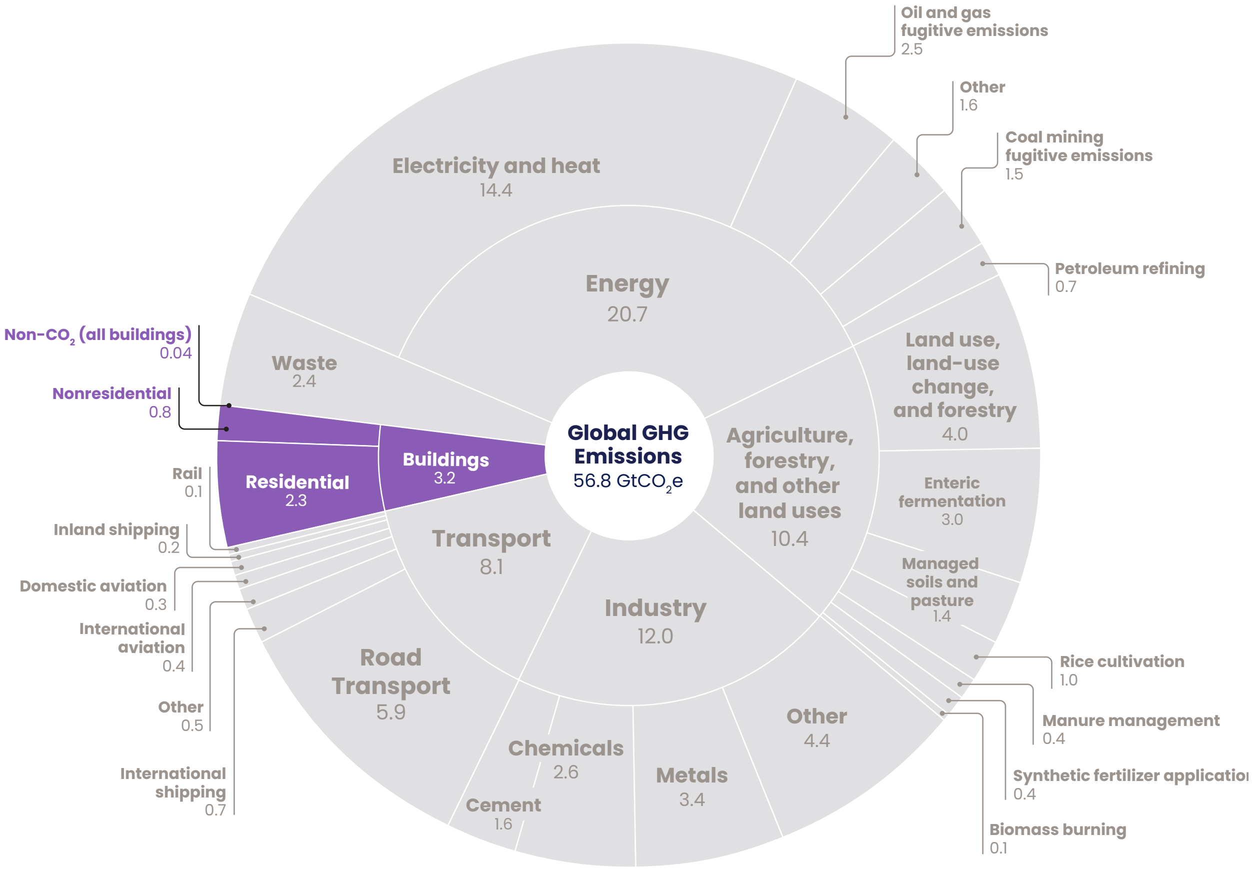
SECTION 3

Buildings

Buildings are the spaces where many carry out the activities of daily life, but these activities, and the buildings themselves, often rely on fossil fuels and are a significant source of GHG emissions. Direct GHG emissions from burning fuel for cooking and heating on-site accounted for an estimated 6 percent of GHGs globally in 2021 (Figure 13). When considering indirect GHG emissions released off-site from the production of electricity and heat that is used for heating, cooling, cooking, lighting, electronics, and other activities in buildings, these GHG emissions roughly triple from about 3 $GtCO_2$ to 9 $GtCO_2$ (Figure 14) (IEA 2022c). Constructing and furnishing buildings generates additional emissions, known as embodied emissions (IPCC 2022b).

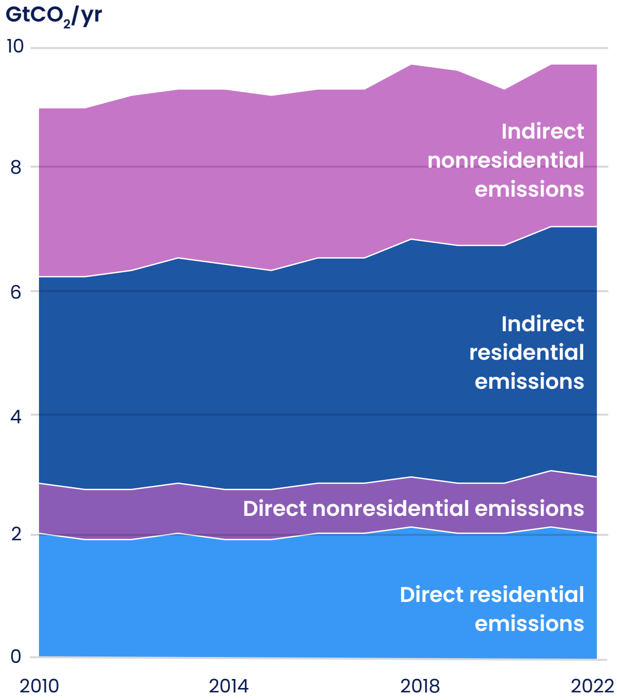
Operational emissions from buildings have risen steadily since 1990, driven predominantly by electricity consumption and floor area growth (Figure 14) (IEA 2022c). Changing behaviors during the COVID-19 pandemic—namely, teleworking following offices closing during lockdowns, as well as the decline in hotel occupancy and restaurant dining—led to a drop of about 3 percent in carbon dioxide (CO_2) emissions from buildings in 2020 compared with the year before, less than the 10 percent drop initially estimated (IEA 2021d; UNEP 2021a; IEA 2023d). CO_2 emissions from building operations have since rebounded to prepandemic levels (IEA 2022c). In 2022, global energy-related CO_2 emissions rose almost 1 percent compared to the previous year but, other than 2020, operational emissions from buildings have remained similar over the last five years (IEA 2023o). Underlying this pattern are, however, geographical differences. In 2022, buildings-related emissions grew significantly in Asia and North America, partly driven by high temperatures driving increased demand for cooling as well as reliance on gas and coal. In Europe, emissions dropped in 2022 because of a combination of warm winter weather and the response to fossil fuel supply disruptions caused by Russia's illegal invasion of Ukraine. European governments are now prioritizing a shift toward renewable energy and other clean fuels, especially for heating (IEA 2023o).

FIGURE 13 | Buildings' contribution to global net anthropogenic GHG emissions in 2021



Notes: CO_2 = carbon dioxide; GHG = greenhouse gas; $GtCO_2e$ = gigatonnes of carbon dioxide equivalent.
Sources: Minx et al. (2021); European Commission and JRC (2022).

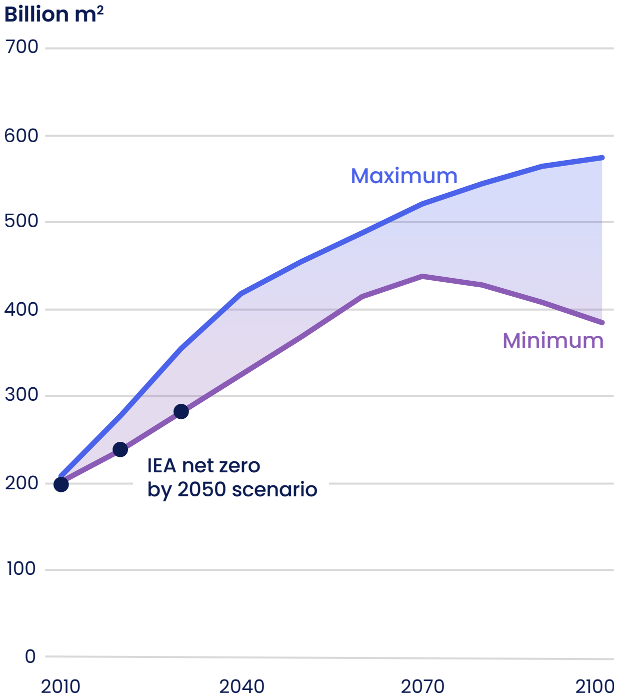
FIGURE 14 | Global direct and indirect CO_2 emissions from buildings



Notes: CO_2 = carbon dioxide; $GtCO_2$/yr = gigatonnes of carbon dioxide per year. Minx et al. (2021) and European Commission and JRC (2022) provide an estimate of direct and indirect GHG emissions from buildings through 2020. Data on indirect GHG emissions from buildings, specifically, are not yet available for 2021. But because they represent such a significant share of this sector's total emissions (67% in 2020), this figure relies on a different dataset than Figure 13. This IEA (2023d) dataset includes data on both indirect and direct emissions from 2010 to 2022 but excludes non-CO_2 emissions. More specifically, these data exclude F-gas emissions from the refrigerants used for refrigeration or in air conditioners and heat pumps. Recent data are not available, but emissions of F-gases from these activities are estimated at just over 500 $MtCO_2e$ in 2016 (Green Cooling Initiative 2023a).

Source: IEA (2023d).

FIGURE 15 | Global floor area growth projections from selected models from the IPCC AR6 scenarios database



Note: AR6 = Sixth Assessment Report; IEA = International Energy Agency; IPCC = Intergovernment Panel on Climate Change; m^2 = square meter. The data are taken from the IPCC AR6 scenario database, using scenarios that are compatible with 1.5°C and fit additional sustainability criteria (CAT 2023a), as well as models that specifically focus on the buildings sector; floor area data from the IEA NZE 2050 scenario are also included (IEA 2021b). This figure shows the range of floor area predictions from the selected AR6 scenarios along with the floor area values from the IEA Net Zero by 2050 scenario, the latter of which tracks the lower bound of the range from the AR6 scenarios. Even though it is now historic, 2020 has multiple estimates of floor area. This is because the model runs were initiated in earlier years and make predictions for 2020 using a set of inputs and assumptions (relating to technology availability, energy supply, climate conditions, and policy decisions, to name a few) (Evans and Hausfather 2018).

Sources: Data from IPCC AR6 scenarios database (Byers et al. 2022) and IEA NZE 2050 (IEA 2021b).

Under current trajectories, emissions from buildings will continue to grow. Total floor area is a primary driver of emissions and is expected to keep expanding in the coming decades (Figure 15). By 2060, floor area could be double what it was in 2020 (UNEP 2017; IEA 2017a). Space heating and cooling are major components of building energy consumption and emissions, and the more floor area there is, the more heating and cooling is needed. As buildings grow in number and size, they will also produce higher embodied emissions due to the greater volume of construction materials used. The amount of floor area and energy used per capita differs vastly among and within countries, often depending on the country's level of wealth and its climatic zone. Much of the growth in floor area is expected to occur in Asia and Africa as standards of living improve. Steps can be taken now to ensure that new building construction goes hand in hand with minimizing CO_2 emissions from construction and with meeting additional demand for thermal comfort (UNEP 2022a). Substantial improvements across buildings are needed to meet the Paris Agreement's goal of limiting the rise in global temperature to 1.5°C. The data that are publicly available indicate that none of the indicators assessed are on track.

Global assessment of progress for buildings

Because buildings vary so much across the globe and depending on their intended use, pathways for decarbonization and the technologies and strategies used will differ significantly by geography and building type. Different climatic zones, for example, require different approaches to meet heating and cooling needs.

TABLE 2 | Summary of global progress toward buildings targets

INDICATOR	MOST RECENT DATA POINT (YEAR)	2030 TARGET	2035 TARGET	2050 TARGET	LIKELIHOOD OF FOLLOWING AN S-CURVE	ACCELERATION FACTOR	STATUS
Energy intensity of building operations (kWh/m^2)	140 (2022)	85–120	N/A	55–80	↗	3x	✗
Carbon intensity of building operations ($kgCO_2/m^2$)	38 (2022)	13–16	N/A	0–2	⤴	4x	✗
Retrofitting rate of buildings (%/yr)	<1 (2019)	2.5–3.5	3.5 (2040)	N/A	↗	Insufficient data	?
Share of new buildings that are zero-carbon in operation (%)	5 (2020)	100	100	100	⤴	Insufficient data	?

Notes: $kgCO_2/m^2$ = kilogram of carbon dioxide per square meter; kWh/m^2 = kilowatt-hour per square meter; yr = year. See Jaeger et al. (2023) for more information on methods selecting for targets, indicators, and datasets, as well as our approach for assessing progress.

Sources: Historical data from IEA (2020c, 2021c, 2021b, 2023g, 2023d); targets from CAT (2020b, 2023a).

Mitigation strategies can depend on the type of building (residential or commercial), whether it exists or is yet to be built, what infrastructure (such as gas connections) are available, and what type of fuels are used to power it. Still, across these contexts, decarbonizing the buildings sector at the global level will require four interrelated shifts (Table 2): improving the efficiency of energy use in buildings, decarbonizing energy use, retrofitting the existing building stock, and ensuring that new buildings are constructed to be zero-carbon in operation. New buildings need to be designed not only to operate with zero carbon emissions but also to minimize their embodied carbon; for example, by switching to low- and zero-carbon materials and construction processes, and recycling materials after demolition. An indicator to track embodied emissions is not included in this report due to a lack of data, but efforts to collect more data on embodied carbon will help make tracking this fundamental transition easier in the future.

Underpinning all of these shifts is sufficiency, used by the IPCC to mean reducing demand alongside changing the way we use existing space (e.g., by ensuring more evenly distributed floor area per capita, using empty buildings for new purposes, and making buildings multifunctional to increase building occupancy and use over time) and prioritizing retrofitting and repurposing over constructing new space wherever possible (IPCC 2022b). Achieving sufficiency will make it easier to decarbonize the buildings sector (Bernhardt 2023). In keeping with this, improving buildings' energy efficiency and decarbonizing energy use are two of the main mitigation goals to drive decarbonization of building operations; these will need to be achieved by retrofitting existing buildings and constructing new buildings to be zero-carbon in operation. Given the urgency of reducing emissions, all new buildings should be zero-carbon in operation (energy efficient and not reliant on fossil fuel–powered technology) while minimizing emissions from construction and furnishing (WorldGBC 2019). Decarbonizing existing buildings will require a high annual rate of deep retrofits of building envelopes using materials with low embodied carbon and heating systems that drastically improve energy efficiency and replace equipment with zero-carbon options.

While this report focuses on mitigation, buildings also play a fundamental role in adaptation to climate change, where affordable and resilient housing will help communities facing the impacts of climate change (WorldGBC 2023d). Additionally, this section does not address urban planning and the wider built environment, though changes in these contexts impact buildings, such as creating more green spaces, which lower overall temperatures in cities and reduce the need for active cooling.

Improve energy efficiency

Reducing the energy intensity of buildings, defined as the amount of energy used per square meter (m^2) of floor area, helps to minimize overall energy demand from the sector and, as a result, makes it easier to decarbonize the energy supply by meeting remaining energy needs with renewables. These aims can be achieved through efficiency improvements, including changing use patterns, altering the building envelope (such as by adding insulation) to reduce active heating and cooling needs, and upgrading to more efficient technologies (such as electrical appliances and lighting) (IPCC 2022b).

Adopting strategies to improve energy efficiency has the potential to deliver a 42 percent emissions reduction in the buildings sector, while also supporting decarbonization due to decreased energy demand per unit of floor area or end use; sufficiency, which includes reducing energy and material demand, can deliver a 10 percent emissions reduction (IPCC 2022c). The energy intensity indicator that we track includes energy efficiency as well as other improvements, such as behavioral change around energy use (e.g., comfort temperatures and ratio of floor area per capita). The zero-carbon and energy-efficient technologies needed already exist and are fairly mature (IEA 2019; Ürge-Vorsatz et al. 2020), though adoption of these innovations needs to be tailored to each building and its location. Such readily available measures include improving thermal efficiency by installing double- or triple-glazed windows, upgrading roof and wall insulation, orienting new buildings to maximize shade and reduce thermal heat gain, installing shutters and blinds, putting in cool or green roofs, and ventilating properly. Digital sensors and controls can further optimize energy use by monitoring and regulating temperature (IEA 2019).

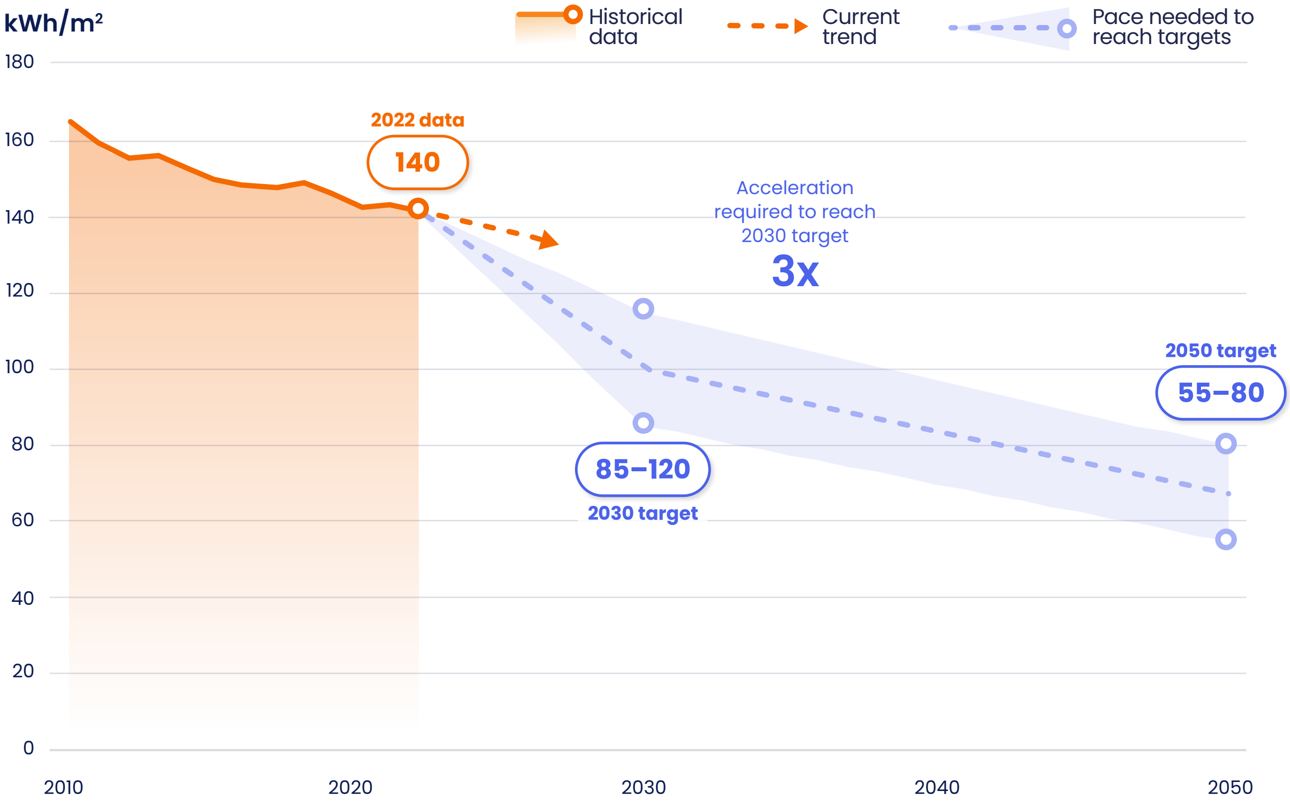
BUILDINGS INDICATOR 1:
Energy intensity of building operations (kWh/m²)

- **Targets:** The energy intensity of building operations drops to 85–120 kilowatt-hours per square meter (kWh/m²) by 2030 and to 55–80 kWh/m² by 2050.

Globally, the energy intensity of building operations declined by 20 percent from 2000 to 2015, but this progress has recently slowed and remains well off track (IEA 2020a). The sector saw only an additional 2.5 percent decline in energy intensity from 2015 to 2019, but overall energy demand growth slowed over the last three years of available data (2020–22), which translates into an improved energy intensity (IEA 2022c). Multiple competing factors are driving these trends, including the recent COVID-19 and energy crises, interannual variability in weather patterns changing heating and cooling needs, and changing behaviors, such as increased uptake of digital devices. To achieve the 2030 target, gains made from 2018 to 2022 would need to accelerate by a factor of 3 (Figure 16).

FIGURE 16 | Historical progress toward 2030 and 2050 targets for energy intensity of building operations

Right Direction, Well Off Track **S-Curve Unlikely**



Note: kWh/m² = kilowatt-hour per square meter. See Jaeger et al. (2023) for more information on methods for selecting targets, indicators, and datasets, as well as our approach for assessing progress.

Sources: Historical data from IEA (2023g); targets from CAT (2023a).

Energy intensities in Europe, North America, and other developed regions are improving at a rate similar to the global average trend. Some developing Asian countries are lowering energy intensity more quickly, while most other regions, including China, have managed only small improvements (IEA 2020a). Space and water heating dominate energy demand from buildings at the global level, together accounting for close to half of demand in 2022 (IEA 2023i). However, energy demand has grown more quickly for other end uses in buildings since 1990, especially connected and small appliances (up 280 percent), cooking (up 89 percent), and cooling (up 75 percent) (IPCC 2022b).

Some future increases in energy use from the buildings sector will be driven by improvements in energy access. Sustainable Development Goal 7 (SDG7) calls for "ensuring access to affordable, reliable, sustainable and modern energy for all" by 2030. It aims for universal energy access through widespread electrification, powered as much as possible by zero-carbon energy sources and clean fuel sources for cooking (UNDESA n.d.; IPCC 2022b). As it stands, 680 million people globally (the majority of them living in Africa) do not have electricity (down from 733 million in 2020), and 2.4 billion people are not using clean fuels for cooking (IEA et al. 2022b; IEA 2023p; UNEP 2022a). Between 2018 and 2020, 57 million people gained access to electricity, but progress needs to accelerate substantially in order to reach universal access (Systems Change Lab 2022). Addressing equity in energy access goes hand in hand with ensuring that energy efficiency improvements are broadly accessible. It is important to set up guidance and financial support for better energy efficiency improvements, energy transitions, and decarbonization to meet energy needs with clean fuels but without further burdening vulnerable households.

Decarbonize building operations

Effectively implemented and widespread energy efficiency improvements can greatly reduce energy demand and global emissions from buildings (IPCC 2022b, 2022c). However, energy efficiency improvements alone will not achieve the Paris Agreement limit and need to be accompanied by global efforts to decarbonize the remaining energy used in buildings. Energy use can be decarbonized by switching the energy source for heating and cooking equipment (i.e., from fossil fuels to electric power) and decarbonizing the power supply (see the Power section). Electrification is an important step to decarbonize energy use in buildings (Bernhardt 2023), and decarbonization of the power sector will be necessary for decarbonization in buildings. Incorporating renewable energy infrastructure in buildings will additionally help to provide clean power and energy; this includes solar panels for on-site power generation and solar thermal collectors that can be used to heat water (IPCC 2022b, 2022c; IEA 2022e).

BUILDINGS INDICATOR 2:

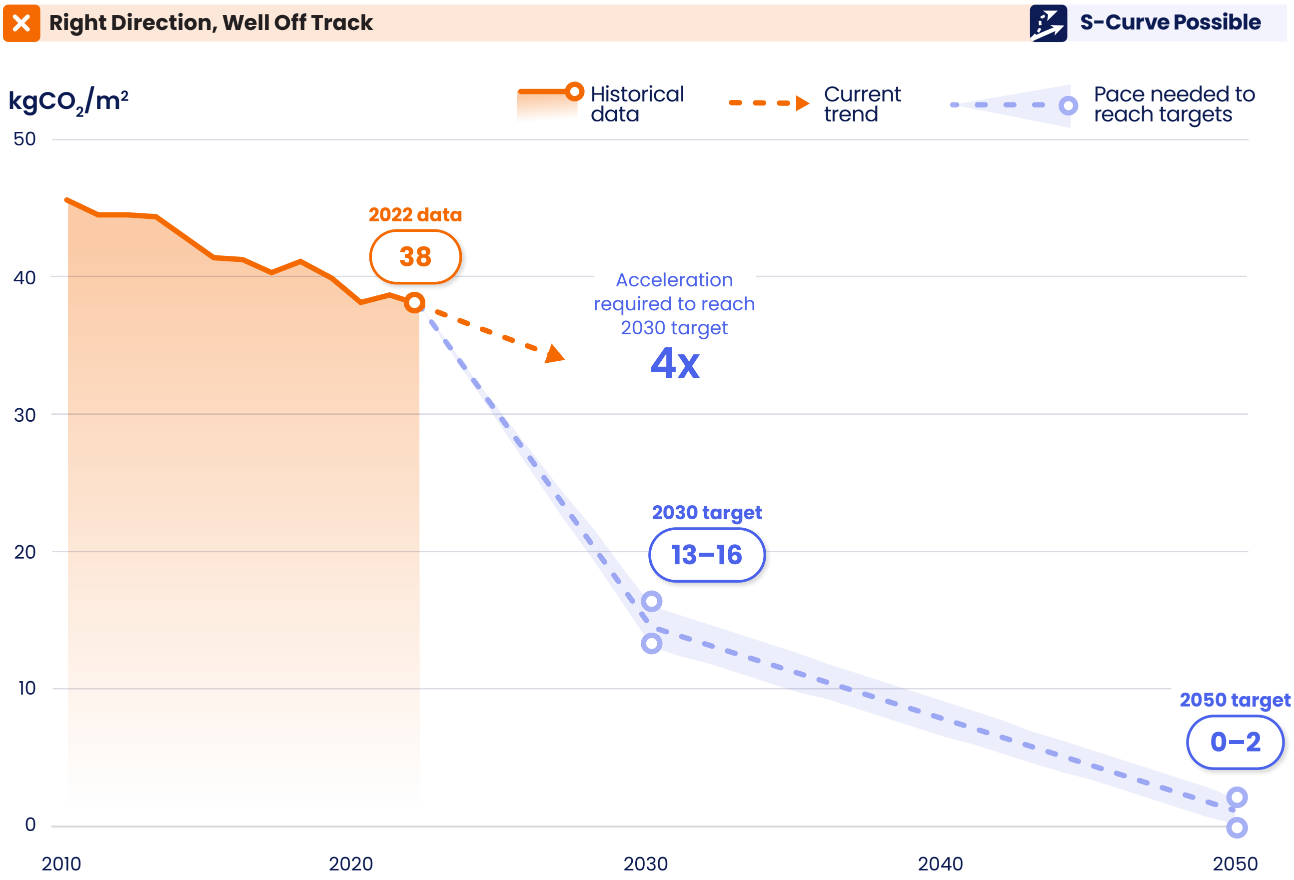
Carbon intensity of building operations ($kgCO_2/m^2$)

- **Targets:** The carbon intensity of building operations falls to 13–16 kilograms of carbon dioxide per square meter ($kgCO_2/m^2$) by 2030 and to 0–2 $kgCO_2/m^2$ by 2050.

The carbon intensity of buildings is calculated by dividing total CO_2 emitted from energy use, including electricity, by global total floor area. This indicator differs from the energy intensity of buildings in that it reflects not just how much energy they use, relative to their size, but also where that energy comes from and how much carbon is emitted from producing and consuming that energy. For all buildings (residential and commercial floor area combined), average global carbon intensity has steadily decreased since 2000 (Figure 17). However, recent declines in carbon intensity remain well off track and have been more than offset by increases in floor area, which rose on average by 2 percent per year between 2010 and 2020. As a result, CO_2 emissions from buildings have remained relatively level since 2010 (Figure 14) (IEA 2023d, 2023j). To achieve the 2030 target, gains made from 2018 to 2022 would need to accelerate by a factor of roughly 4.

Currently, space heating is the greatest contributor to emissions intensity from buildings, but space cooling needs are quickly growing in many places as people gain access to cooling services who did not have them previously. As temperatures rise, space cooling will likely contribute a greater share of emissions in the future (IEA 2019, 2022k, 2022r). Greater electrification of building energy end uses, especially heating systems, is a promising development, but the source of electricity also needs to be decarbonized to reduce emissions.

FIGURE 17 | Historical progress toward 2030 and 2050 targets for carbon intensity of building operations



Note: $kgCO_2/m^2$ = kilogram of carbon dioxide per square meter. See Jaeger et al. (2023) for more information on methods for selecting targets, indicators, and datasets, as well as our approach for assessing progress.

Sources: Historical data from IEA (2023g, 2023d); targets from CAT (2023a).

Retrofit existing buildings

Reducing existing buildings' energy and emissions intensity will require deep retrofits. Retrofitting includes energy efficiency improvements, such as the installation of double-glazed windows to improve heat retention, or upgrading insulation, and decarbonization measures, such as replacing fossil fuel–based heating systems with electric systems, primarily heat pumps. It also means upgrading energy-consuming devices such as appliances to more efficient versions and switching to light-emitting diode (LED) lighting systems (IEA 2022a, 2022n). Altering the building envelope (meaning its structural elements, such as walls and windows) and upgrading systems (such as heating or cooling) have high up-front costs that are often a barrier to their implementation. However, making these changes to the envelope of buildings has a large, direct impact on the energy efficiency and emissions of buildings, consequently reducing utility bills, and can make retrofitting projects worth the initial investment (LETI 2021; IEA 2022p; WorldGBC 2022a). Retrofitting will be most applicable in countries where most of the building stock that will exist in 2050 has already been built—as is the case in Australia, Canada, Europe, the United States, and increasingly China (Liu et al. 2020; IEA 2019). Around 85–95 percent of Europe's building stock for 2050 already exists today (European Commission 2020).

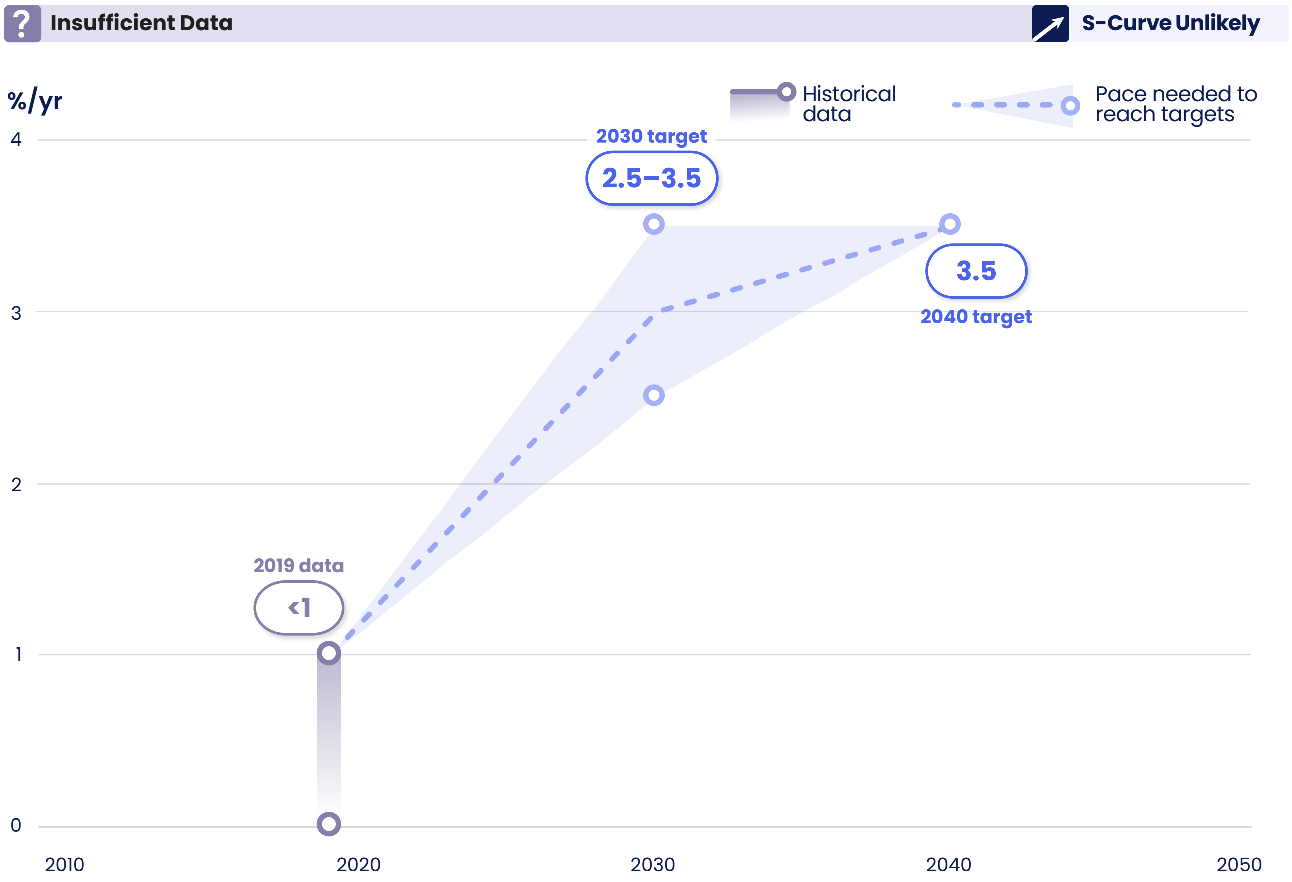
BUILDINGS INDICATOR 3:

Retrofitting rate of buildings (%/yr)

- **Targets:** The annual global deep retrofitting rate of buildings reaches 2.5–3.5 percent by 2030 and 3.5 percent by 2040; all buildings are well insulated and fitted with zero-carbon technologies by 2050.

Meeting the 1.5°C temperature limit means that all building stock will need to be net-zero carbon in operation by 2050 at the latest, which means that all existing buildings that are not net zero need to undergo a deep retrofit to that standard before then. Doing so requires a retrofitting rate of 2.5–3.5 percent of existing buildings each year, with higher rates required in developed countries with substantial existing stock (CAT 2020b).

FIGURE 18 | Historical progress toward 2030 and 2040 targets for retrofitting rate of buildings



Note: yr = year. See Jaeger et al. (2023) for more information on methods for selecting targets, indicators, and datasets, as well as our approach for assessing progress.

Sources: Historical data from IEA (2020c, 2021c); targets from CAT (2020b).

Currently, according to the IEA, less than 1 percent of buildings are retrofitted every year (European Commission 2022c; IEA 2020c, 2021c), which is well below what is required to meet the targets for deep retrofitting (Figure 18). Data on deep retrofitting rates do not exist for many countries, and, where data are available, the information is usually for single years (European Commission 2022c). Due to insufficient data, it is not possible to give a quantitative estimate of how much deep retrofitting needs to accelerate to meet the 2030 target, but it is clear that the pace needs to increase drastically in the coming decade.

Construct zero-carbon new buildings

New buildings can help mitigate emissions, because decisions made during the design process will impact a building's emissions over its lifetime. Emissions released during the process of making a building, replacing components and retrofitting, and demolishing a building at the end of its lifetime are known as embodied emissions (see Box 6). Constructing new buildings is emissions-intensive because of the energy needed for construction, including transportation of materials, powering of construction machinery, production of the materials used, and generation of waste during the construction process. Most of the emissions from construction come from only six materials but can make up almost 50 percent of the entire life-cycle emissions of a building (WBCSD 2021).

Access to adequate housing is a fundamental human right (UNOHCHR 2014) but remains a challenge for many, with climate change impacts posing growing threats to this right. It is necessary to build new, zero-carbon housing that is also safe, affordable, and resilient to the impacts of climate change, particularly for the most vulnerable communities, such as those who live in informal housing. Campaigns such as Roof over Our Heads, which was launched at COP27 with support from the High-Level Champions (2022a) of the UN Framework Convention on Climate Change (UNFCCC), seeks to help people living in informal housing, involving women and local communities from the start in shaping the strategy and its implementation.

BOX 6 | Tackling embodied emissions

We already possess the knowledge and technologies needed to construct buildings that operate with zero emissions, whereas embodied emissions from constructing those buildings can be more challenging to eliminate. The principle of "Avoid, Shift, Improve" can be applied to embodied emissions, where Avoid means build less and better; Shift means using alternative building materials; and Improve means decarbonizing conventional materials (PEEB 2021). Avoiding emissions through building less and better means repurposing existing buildings wherever possible, adhering to sufficiency principles, and designing buildings in a material-efficient manner, such as rectangular geometries instead of circles (WBCSD and Arup 2023). Many alternative construction materials have already existed for a long time (for example, wood, bamboo, or clay), while others are being newly (re)developed for modern buildings (for example, straw, hemp, recycled plastic, or even fungi). Many of these materials are bio-based and not only have lower emissions than traditional construction materials but may even act as a net carbon sink over the building's lifetime (Churkina et al. 2020). However, a full life-cycle analysis is needed to ensure that the use of bio-based materials, particularly timber, does not actually lead to net emissions or have other negative environmental consequences, such as loss of biodiversity (Searchinger et al. 2023). Finally, the emissions intensity of conventional construction materials can be improved. Two of these core building materials—cement and steel—are covered in the Industry section. Applying "circular economy" principles can also help reduce embodied emissions. This means planning, constructing, and furnishing buildings to allow them to be repurposed for different uses at a later date, or ensuring that their materials can be recycled or reused at the end of their lifetimes (UNEP 2022a; Naden 2020).

Much will hinge on how new buildings in developing countries are constructed. In many of these countries, floor area per capita is still low, but rapid urbanization, rising populations, economic growth, and access to adequate housing will fuel demand for new floor space (Figure 15) (UNDESA 2022). Eighty percent of floor area growth to 2030 is anticipated in emerging market and developing economies, with building booms expected in Asia, Africa, and Latin America (IPCC 2022b; UNEP 2022a; IEA 2023j). In Africa, an estimated 70 percent of the building stock that will exist in 2040 is expected to be constructed in the coming two decades (UNEP 2022a). This rapid growth in developing countries will require particular attention to the design and construction of new buildings, including their choice of materials, material efficiency, and reuse of materials to minimize embodied carbon (WorldGBC 2020). One factor that will drive construction in developing countries is an acute need for adequate housing.

It is currently difficult to track progress in reducing embodied emissions at the global level because few data have been collated, even for individual buildings (UNEP 2022a). More recently, initiatives, regions, and companies are starting to track whole-life carbon emissions—meaning the emissions from a building's entire life cycle, including construction, operation, and demolition—and more information is becoming available for individual buildings or neighborhoods (WBCSD 2021; UNEP 2022a). Improving data availability for buildings, and harmonizing approaches to building life-cycle assessments, would both help inform and improve best practices and decarbonization strategies and enable progress tracking in the future; moreover, it is a vital stepping stone toward policy and regulation of whole life-cycle carbon (WorldGBC 2022d; Astle et al. 2023). A new initiative in Europe is piloting approaches that bring industry, researchers, and lawmakers together to codevelop national benchmarks for policymaking on whole life-cycle carbon where these do not yet exist (Smith Innovation 2022). Building passports—repositories that contain all life-cycle data of individual buildings—are another way to build knowledge on whole life-cycle carbon and examples of success (Tonks 2023; GlobalABC et al. 2021). They are a tool to collect and store information from and for a variety of stakeholders about a building from its whole life cycle, meaning throughout the construction and operation phases (GlobalABC et al. 2021). They are useful for developing understanding, increasing transparency, and supporting stakeholders' decision-making about a given building. Despite data gaps, the rising production of steel and cement to build additional floor area continues to drive emissions, and many of the principles of low-carbon design remain to be mandated or become common practice in many countries. Much therefore remains to be done in reducing embodied emissions in buildings.

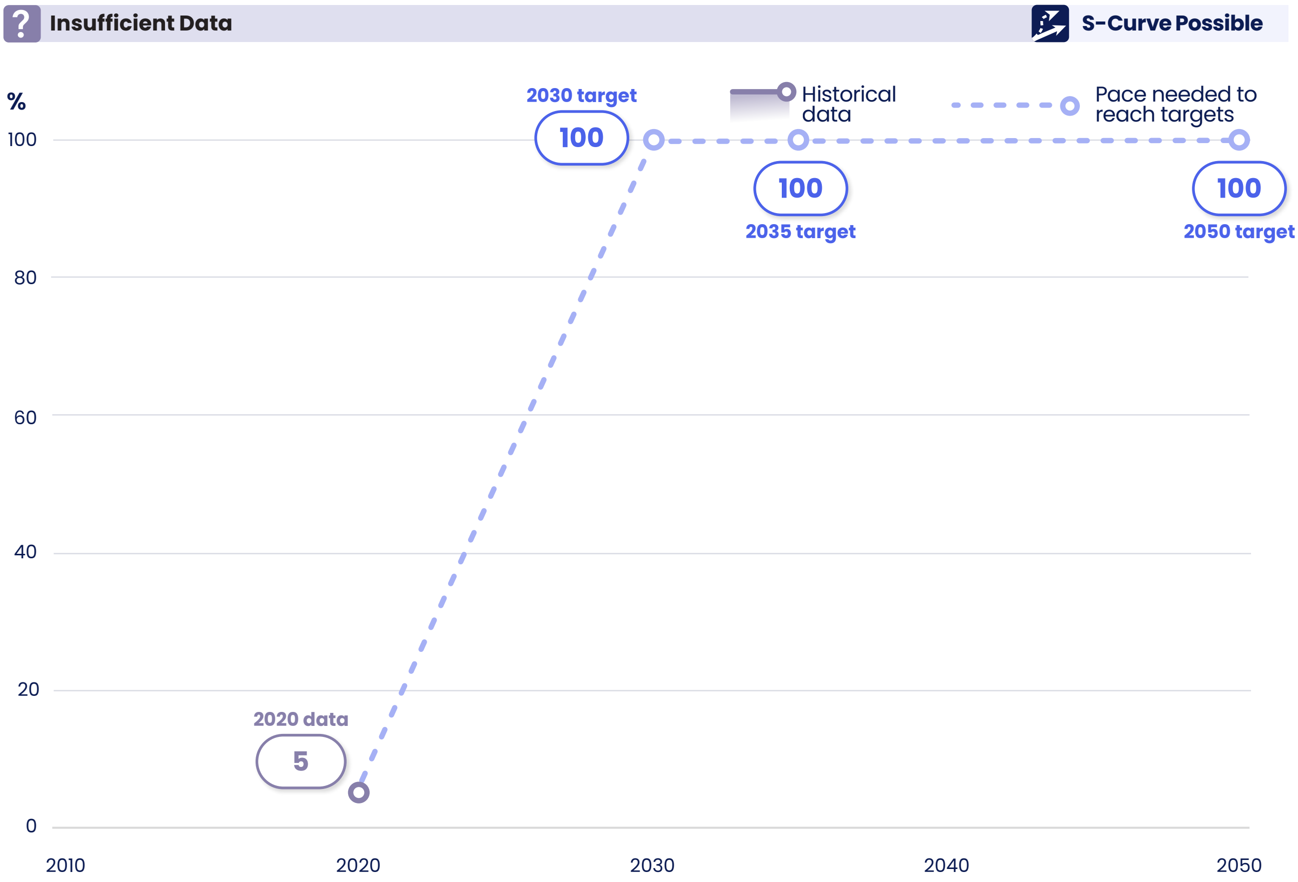
BUILDINGS INDICATOR 4:
Share of new buildings that are zero-carbon in operation (%)

- **Targets:** All new buildings are zero-carbon in operation by 2030, with the world sustaining this target through 2050.[23]

To limit warming to 1.5°C, all new buildings must be net-zero carbon in operation—either from the start or following decarbonization of the power sector (IEA 2021b; UNEP 2022a; CAT 2020b). Building to zero-carbon specifications is much less expensive than retrofitting over the next two to three decades (Currie & Brown and AECOM 2019; IEA 2020c). No dataset is currently available for tracking the share of new buildings that are zero carbon in operation. Progress in data collection has been made, though. For example, a sustainable construction database was established in the Colombian city of Medellín to collect information on floor area, emissions, and building projects, alongside policies on sustainable construction and retrofitting (C40 2022).

However, many new buildings, including those being constructed in developed countries, are still built with fossil fuel–based heating systems, such as gas boilers, and lack on-site renewables, such as solar panels. For example, in Germany, where the share of fossil fuel heating in new buildings is decreasing, 16 percent of new residential buildings approved in early 2022 still had gas as the primary heating source (Federal Statistical Office 2022). Insufficient data means it is not possible to assess whether or not this indicator is on track. However, given the available evidence that fossil fuel–based heating installations continue, it is clear that substantial change and progress is needed to meet the 2030 and 2050 targets (Figure 19).

FIGURE 19 | Historical progress toward 2030, 2035, and 2050 targets for share of new buildings that are zero-carbon in operation



Note: See Jaeger et al. (2023) for more information on methods for selecting targets, indicators, and datasets, as well as our approach for assessing progress.

Sources: Historical data from IEA (2021b); targets from CAT (2020b).

Recent developments across buildings

Though progress on indicators in the building sector has been slow, some positive signals are emerging. In particular, some recent developments are overarching across all of the needed shifts, inviting optimism about progress on all. Change will hinge on achieving the enabling factors outlined in *State of Climate Action 2022* (Boehm et al. 2022), which describe the kinds of actions needed to improve energy efficiency and decarbonize building operation across existing and new buildings. These enabling conditions relate to technology and other innovations, increased regulation to deliver on goals and help bridge gaps between actors, strengthened institutions, and strong leadership in making change.

Decarbonization roadmaps are an essential tool for developing and implementing context-specific strategies to decarbonize the buildings sector. While decarbonization roadmaps are not specific to the buildings sector, they are especially important for buildings in both signifying and spurring greater action on mitigation. Roadmaps are increasingly being developed at city, regional (the GlobalABC has regional roadmaps for Africa, Asia, and Latin America), and national levels (WorldGBC's 2023 Advancing Net Zero Status Report maps the existing whole life-cycle carbon roadmaps around the world) (GlobalABC, IEA, and UNEP 2020; WorldGBC 2023a). These strategies tackle both specific and sector-wide challenges in decarbonizing buildings, both in terms of embodied and operational emissions, that are vital for transforming this sector. They identify possible pathways, guide policymakers, and locate synergies between different actors (UNEP 2022a). In June 2022, Colombia released its National Roadmap for Net Zero Carbon Buildings, which explains specific actions a range of actors need to take to achieve the country's goal of ensuring that by 2030 all new buildings, and by 2050 all buildings, are net zero–aligned in both formal and informal construction (Rakes 2022b). Throughout 2021 and 2022, 10 Green Building Councils in Europe launched similar net-zero whole life-cycle carbon roadmaps (WorldGBC 2022c). However, the existence of a roadmap does not always mean that it has been translated into actionable policies that can be monitored and enforced (Mata et al. 2020).

One way to ensure that strategies translate into action is to establish strong regulatory frameworks, such as those regulating whole life-cycle carbon in Denmark, France, Finland, the Netherlands, and Norway (WorldGBC 2019). Legislative barriers, including lack of regulation or support from governments, are some of the biggest hurdles to overcome (Ohene et al. 2022). While context-specific regulation is needed at the national level, international standards set global, common principles. These can form a basis for designing policies and strategies. They offer a way to assess both the current status of building practices, policies and regulations, and progress toward implementing more sustainable standards (Naden 2020).

Adequate financing is also needed to overcome economic barriers to decarbonizing the buildings sector and implementing roadmaps (Ohene et al. 2022). In 2021, investments in building efficiency jumped 21 percent as the construction sector rebounded from the COVID-19 pandemic, after years of slow financing mobilization (IEA 2022c). However, as construction markets grow in different parts of the world, continued high rates of investment in zero-carbon options will be important. The IPCC highlights that investments in energy efficiency and renewable heat totaling $711 billion will be required annually from 2026 to 2030 to decarbonize the buildings sector, compared to $250 billion invested in 2022 (IPCC 2022c; IEA 2023j). Accelerating the transition will also require investments in developing institutional capacity. Some progress has been made in this regard. The Building Efficiency Accelerator (BEA 2023), launched in 2015 by World Resources Institute, seeks to build institutional capacity at the local and regional level in partner cities around the world, tackling institutional and economic barriers that prevent the scale-up of energy efficiency improvements. The program does this by supporting public-private partnerships. World Resources Institute established the Zero Carbon Building Accelerator (ZCBA) in Turkey and Colombia in 2021 to follow on the work from the BEA and provide a platform for knowledge-sharing to drive roadmap development and policy implementation tailored to local contexts (Rakes 2022a).

While there has not been much visible progress on the high-level indicators for decarbonizing the buildings sector tracked in this report, buildings are becoming a greater part of the conversation on sectoral mitigation at the global level. The *2022 Global Status Report for Buildings and Construction* from the Global Alliance for Buildings and Construction highlighted that the number of times countries mention buildings in their NDCs shot up from 88 in 2015 to 158, which is about 80 percent of countries, in 2021 (UNEP 2022a). While NDCs may not be the best measure of action taken, and their level of detail varies, they are a way for governments to demonstrate their intentions and commitments, and they also serve as a guide for local government on national priorities. At COP26 in 2021, the United Nations Climate Change High-Level Champions launched the 2030 Breakthroughs, an initiative that presents sectoral targets to align and raise both ambition and action of nonstate actors. A "Buildings Breakthrough" is set to be launched ahead of

COP28 this year and will form a new part of the existing "Breakthrough Agenda," also initiated at COP26. The Buildings Breakthrough, led by France and Morocco, will provide a platform for international collaboration between national governments to unlock action in the sector. Both the 2030 Breakthroughs and the Buildings Breakthrough indicate the raising of buildings' profile on the global agenda, which is fundamental to ensure that the sector receives appropriate attention to drive forward mitigation action.

Recent developments in improving energy efficiency

Regulation is a fundamental tool for reducing buildings' energy intensity and pushing the sector toward alignment with the Paris Agreement limit of 1.5°C (Boehm et al. 2022; IEA 2021d; Economidou et al. 2020), and building energy codes and Minimum Energy Performance Standards are important regulatory instruments to drive changes in energy use. Currently, 79 countries, which are home to 60 percent of the world's population, have adopted these energy codes, though only 26 percent of these codes include mandatory regulations, and not all of these regulations are strongly enforced. Recent progress in expanding coverage remains slow, with only six additional countries implementing these standards since 2018 (CAT 2022c; UNEP 2022a, 2020a). Toolkits, like those hosted by the Getting to Zero Forum (2023), can help relevant actors develop codes by providing guidelines and examples, as well as by connecting users with resources and organizations that can support this process. The WorldGBC's "Global Policy Principles for a Sustainable Built Environment" outlines how regulations can be supported by information and incentives to not only meet climate targets but simultaneously address sustainable development goals by focusing on seven core principles, including carbon, health, resilience, and biodiversity (WorldGBC 2023c). Developing and implementing regulations requires institutional capacity (CAT 2022c). In the United States, the Inflation Reduction Act includes $90 million in funding for a National Energy Codes Collaborative to support jurisdictions in developing up-to-date building energy codes (U.S. DOE 2023).

Recent developments in decarbonizing building operations

As heating and cooling are major drivers of emissions, and therefore carbon intensity, from the buildings sector, these components will be the main focus of the following paragraphs (IEA 2022k). Recent progress toward the phase-out of fossil fuels for heating has mostly occurred in the United States and Europe (IEA 2022k). In the European Union, the Energy Performance of Buildings Directive (EPBD) is part of a suite of policies aimed at reducing emissions in the European Union and transitioning the bloc toward a sustainable future. The latest proposed changes to the EPBD, which are not yet finalized but could be significant if passed, would ban the use of fossil fuels for heating in new buildings and renovation projects immediately and also require a complete phase-out of fossil fuels for heating by 2035 (European Parliament 2023d). Regulation aimed at phasing out fossil fuels goes hand in hand with promotion of alternative technologies. The REPowerEU plan sets out a path toward energy independence and the transition to a clean energy system. It sets the goal of installing 10 million heat pumps over five years, which would mean a doubling in the rate of heat pump installations (European Commission 2022b). The REPowerEU plan was introduced following Russia's invasion of Ukraine and aims to decrease dependence on fossil fuels from Russia and to support the development of renewable energy in Europe. Alongside supporting heating decarbonization, REPowerEU includes a route to ensure a just transition for those working in the sector. Under its "Pact for Skills," the plan contains requirements for job creation, with a focus on retraining, for example by reskilling people who perform gas boiler installations so they can continue to be employed installing heat pumps and other renewable energy technologies (DG Energy 2023).

These kinds of government policies and programs have already encouraged an uptake in adoption of new technologies. In the past year alone, sales of heat pumps rose 38 percent in Europe and 11 percent globally (Rosenow and Gibb 2023; Monschauer et al. 2023). One country where the impact of regulations is already being seen is Poland, which has experienced a massive scale-up of solar PV and heat pump installations in recent years (see Box 7). Heat pumps are a fundamental technology for enabling the decarbonization of heating, as well as cooling, in the buildings sector. They are an efficient, electric-powered technology that captures existing heat from the air, water, or ground to heat a building when the weather is cold. The growth of heat pumps, which would likely follow an S-curve, could help the carbon intensity of building operations decrease in a nonlinear fashion. Some heat pump systems can work in reverse and pump heat out when it is hot; however, this is not possible with all models (IEA 2022j; Energy Saving Trust 2022).

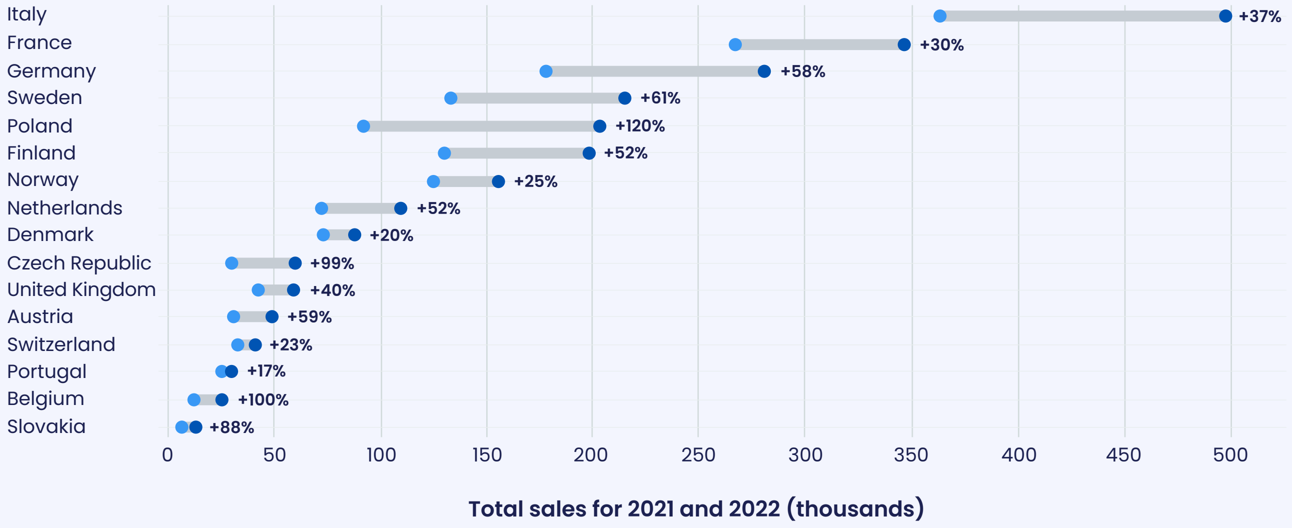
BOX 7 | Rapid scale-up of solar PV and heat pump installations in Poland’s residential sector

In 2020, 77 percent of the coal burned for heating in Europe was used in Poland (Kuzminski et al. 2023; CAT 2022b). Heating accounts for the largest share of Poland’s energy demand, but the country is working toward transitioning from a coal-dominated system to one that is powered by renewables. At the same time, it is reducing energy needs by improving the efficiency of buildings (IEA 2022o). Recent years have witnessed rapid progress toward decarbonizing heating, thanks to a constellation of government programs that subsidize technology installations for generating renewable energy and help consumers replace their home heating systems with newer technology, such as heat pumps. Poland was highly dependent on coal from Russia, so Russia’s invasion of Ukraine has added momentum to the transition to alternative heating systems (IEA 2022o). In 2022, heat pump sales in Poland increased by 120 percent from 2021 (Figure B7.1), which although from a small starting point was the greatest increase seen of countries assessed (Rosenow and Gibb 2023).

The first Polish government program to initiate these changes is the Clean Air Programme, running from 2018 to 2029 (IEA 2022o). Since 2019, the program offers households a tax deduction to incentivize improvements to their homes’ thermal efficiency. It provides households with subsidies to replace their heating systems with more efficient technologies to help tackle air pollution; it additionally includes optional provisions for building efficiency improvements, such as upgrading insulation. The amount of money granted to households is proportional to household income to ensure that lower-income households receive adequate support, and the program helps reduce energy poverty. This program is a good first step, but it could be strengthened. Currently, households can use the money to install a wide range of heating technologies, including fossil-powered heating systems, such as gas boilers if they are more efficient than their existing systems. Phasing out coal and gas boilers and subsidizing only nonfossil fuel–based heating will be necessary for decarbonization. The program could also require steps to improve thermal efficiency that are now only optional by requiring that poorly insulated housing stock be retrofitted with insulation.

Poland is also boosting the provision of renewable electricity through another key mechanism—the “My Electricity” program—in which the Polish government subsidizes the cost of installing solar photovoltaics (PV) in homes by providing households with payments to cover up to 50 percent of the costs (Ministry of Climate and Environment 2019). It has helped propel a 25-fold

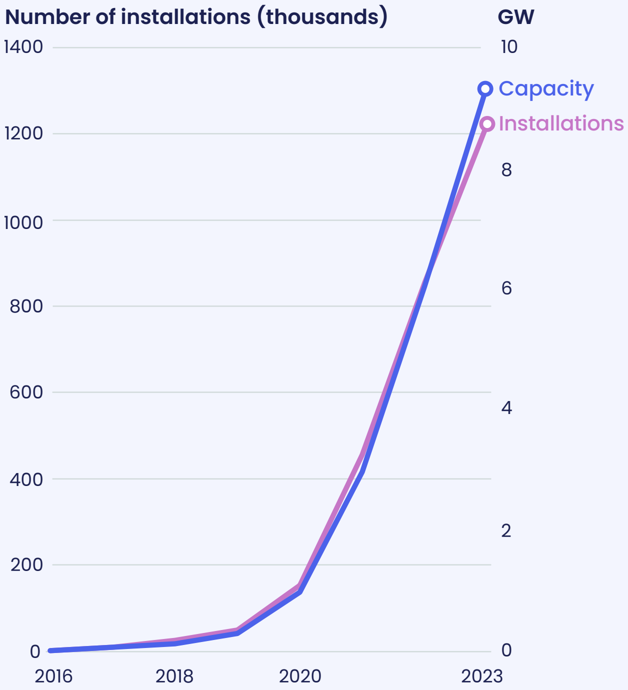
FIGURE B7.1 | Increase in heat pump sales in Europe, showing a 120 percent increase in Poland from 2021 to 2022



Source: Rosenow and Gibb (2023).

BOX 7 | Rapid scale-up of solar PV and heat pump installations in Poland’s residential sector (continued)

FIGURE B7.2 | Annual increase in the number of micro-installations, including solar PV, and installed power capacity in Poland from 2016 to 2023



Notes: GW = gigawatt; PV = photovoltaics. The data are taken from PTPiREE, which tracks the number of microinstallations that are connected to power networks and their installed capacity. Solar PV installations form the majority of these microinstallations.

Source: Data from PTPiREE (2023).

increase in the installed capacity of solar PV from 2017 to 2021 (Figure B7.2) (Olczak et al. 2021). Started in 2019, the scheme is now in its fifth iteration, integrating additional provisions for heat pumps and energy storage during this time (Santos 2022). It also includes a net billing component: producers who sell electricity to the grid get their electric bill reduced the following month (Kuzminski et al. 2023; Kulpa et al. 2021). Combining heating systems that are powered using electricity (heat pumps) with on-site renewable electricity generation technologies (solar PV) is a key strategy for decarbonizing building operations and can reduce both gas and heating costs (SolarPower Europe 2023). However, the My Electricity program does face some obstacles. Most of those installing these systems have been at the upper end of the income scale, because, even with the grant, the up-front cost of installation remains relatively high (Kuzminski et al. 2023; Zdonek et al. 2022). Additionally, this program is currently set to end in 2025, meaning that a longer-term solution is needed (Zdonek et al. 2022).

Positive signals related to heating decarbonization are also emerging in other geographies. For example, in the United States, local governments (those of cities and counties) are driving the phase-out of fossil fuels from heating, with 106 of these introducing policies that encourage, if not mandate, such a transition (Louis-Prescott and Golden 2022).

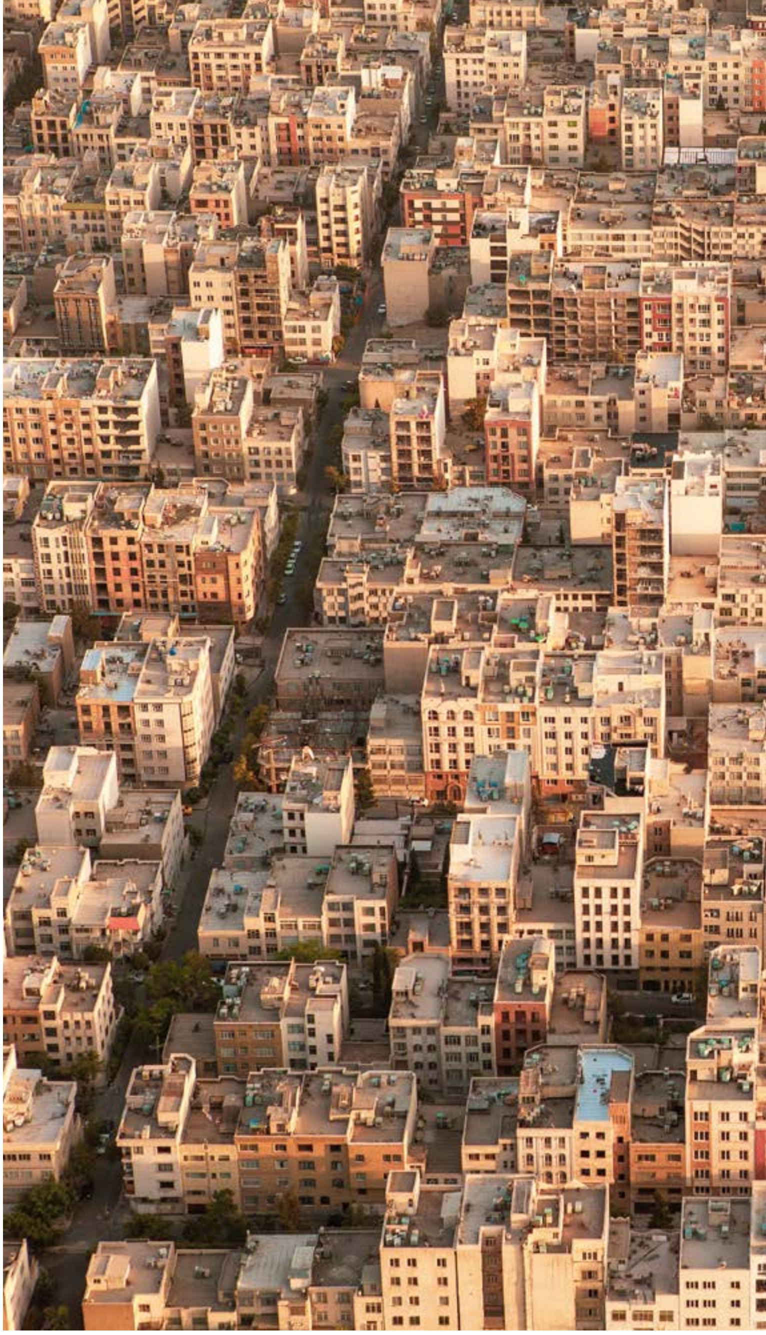
As the world continues to experience higher temperatures, active cooling is becoming increasingly necessary, making up 20 percent of electricity consumption by building globally (IEA 2022r, 2018). Increased air conditioner use will drive up carbon emissions to the extent to which the electricity for it is provided by fossil fuels. Increasing cooling is also currently driving an increase in the release of hydrofluorocarbons (HFCs) with a high global warming potential, as HFCs are commonly used as a refrigerant (UNEP and IEA 2020; Velders et al. 2022). Decarbonizing the electricity supply is particularly challenging for air conditioning, as cooling tends to increase peak electricity load, which needs to be met by dispatchable energy sources. Alternative refrigerants with low or zero global warming potential are available on the market but currently face financial and technical challenges to rapid uptake (Green Cooling Initiative 2023b). Emissions from cooling can also be reduced by reducing active cooling needs, and consequently emissions, through changing building design and retrofitting existing structures; for example, by adding shading to windows, improving sealings, and increasing ventilation (UNEP 2021c). The Programme for Energy Efficiency in Buildings (PEEB) was established at COP22 to help deliver on the Global Alliance for Buildings and Construction’s “Towards Low GHG and Resilient Buildings” roadmap. The PEEB Cool project aims to improve the energy efficiency and resiliency of buildings in African, Asian, Eastern European, and South American partner countries where energy use for space cooling is likely to increase in the coming decades. It will help both by providing finance and offering technical assistance in developing regulations (PEEB 2022); if successful, it could provide a model for future partnerships.

Like heating and cooling, cooking, which accounted for almost 8 percent of final energy demand from buildings in 2020, contributes to GHG emissions, and therefore carbon intensity, from the buildings sector, particularly in Africa and Asia (IEA 2020c, 2021b). Cooking using biomass as fuel both contributes to buildings emissions and creates air pollution that can pose serious health risks (IPCC 2022b). Ensuring access to better cooking technologies and clean fuel sources is a key part of SDG7 (UNDESA n.d.) and will be particularly important in sub-Saharan Africa, where the structure of energy demand in buildings differs substantially from other regions due to high reliance on traditional biomass for cooking and heating (IEA 2022q). Fossil gas is often used as a bridge fuel in replacing traditional biomass, which can create new lock-in; therefore, it is important that in the long term the transition be made to clean cooking technologies using renewables (NewClimate and EED Advisory 2021). The World Bank has mobilized funding to support clean cooking, most recently seeking to help 100 million people gain access to clean cooking technologies this decade through the Clean Cooking Fund (World Bank 2023f; ESMAP 2022).

Recent developments in retrofitting existing buildings

There are positive examples of retrofitting policy moving in the right direction in some regions and countries, including Europe, the United States, and China. Because the high costs and logistics challenges of retrofitting projects are barriers to taking them on, more incentives are needed to increase retrofitting rates. These include regulations mandating minimum retrofitting requirements or performance standards for existing buildings (IEA 2022p) but also financial support for implementation. Financial support is particularly important for low-income households to ensure a decent quality of housing and affordable energy costs. There is a risk of lower-income households losing out further in the technology transition and being left with high-cost fossil heating and cooking in low-efficiency homes.

Despite long-standing legislation on energy efficiency in the buildings sector, retrofitting rates in the European Union have remained at around 1 percent per year (CAT 2022b). However, the European Union now seeks to double the rate of renovations by 2030 with deep retrofits for 35 million residential and commercial buildings, with a focus on public buildings, worst-performing buildings, and heating and cooling decarbonization, that will also help deliver on multiple goals of job creation, improvements to living conditions, and emissions reductions (European Commission n.d.c, 2020). This new push was introduced under the European Union's "Renovation Wave" strategy in 2020 as part of the European Green Deal, a suite of policies to achieve a just, green transition to net zero in Europe and support economic recovery following the COVID-19 pandemic (European Commission 2023a, 2019). Additionally, the European Union's Energy Performance of Buildings Directive is currently undergoing revisions, with proposed measures to increase retrofitting rates, require minimum energy performance, and encourage widespread solar technology installation, among other provisions (European Parliament 2023d; CAT 2022b).



Other countries are also seeing increased attention to retrofitting. In the United States, the recent Inflation Reduction Act targets increasing retrofitting through tax credits and deductions that will help homeowners upgrade and electrify their appliances, install heat pumps and on-site renewables, and replace insulation, doors, and windows (White House 2023). There is also a specific fund to support low-income households to carry out retrofits to improve energy efficiency. China has both a large existing building stock and need for new construction. Its 14th Five-Year Plan, covering the years from 2021 to 2025, seeks to retrofit 350 million square meters of existing buildings as part of its investment in infrastructure and green construction, covering 0.15 percent of current global floor area (ITA 2023).

Recent developments in constructing zero-carbon new buildings

Emissions from the process of constructing buildings have been garnering growing attention recently, including in regions projected to experience large-scale development. One example is C40 Cities' announcement, at COP27, of the Clean Construction Accelerator, which includes targets for achieving a decarbonized construction sector (C40 2023b). COP27 also saw the publication of the Africa Manifesto for Sustainable Cities and the Built Environment, a collaboration by Green Building Councils from 15 African countries, calling for increased access to water and energy, implementation of regulations such as building codes, and application of circular economy practices to building materials, to ensure sustainable, net-zero compatible development that meets people's needs (Africa Regional Network of GBCs 2022; WorldGBC 2022b). Local, sustainable materials and construction methods are a key part of communities' cultural heritage while also being low-emission (UNEP 2022a).

Commitments to construct net-zero carbon buildings have multiplied in recent years. For example, participation has increased in declarations like the "Net Zero Carbon Buildings Declaration" from C40 Cities (which has 29 signatory cities) and the "Net Zero Carbon Buildings Commitment" from the World Green Building Council (with 172 signatories from businesses, cities, governments, and other organizations). Other increasingly prominent initiatives directed toward nonstate actors and local governments include Race to Zero, Cities Race to Zero, and Cities Race to Resilience (C40 2018, 2023a; WorldGBC 2021, 2023b). Public commitments such as these are important, but ensuring implementation will be needed to get the sector on track, meaning that greater action is required to ensure that decarbonization goals are met (WorldGBC 2023b).

Ensuring implementation in the buildings sector implies a need for clear, enforced regulation through updated building codes. An effective building code needs to have a clear cycle of strengthening toward a highly energy efficient, zero-carbon standard over time. Performance-based building codes focus on the outcome and are more adaptable to local circumstances. To date, many building codes focus on operational emissions only but will need to address both operational and embodied emissions for new buildings. In France, the RE2020 regulations seek to reduce embodied emissions through a building's whole life cycle through a cap on emissions that decreases over time (Agora Energiewende 2022). In additional to national regulations, subnational authorities such as city and local jurisdictions are well-positioned to mandate whole life-cycle carbon assessments in policies.

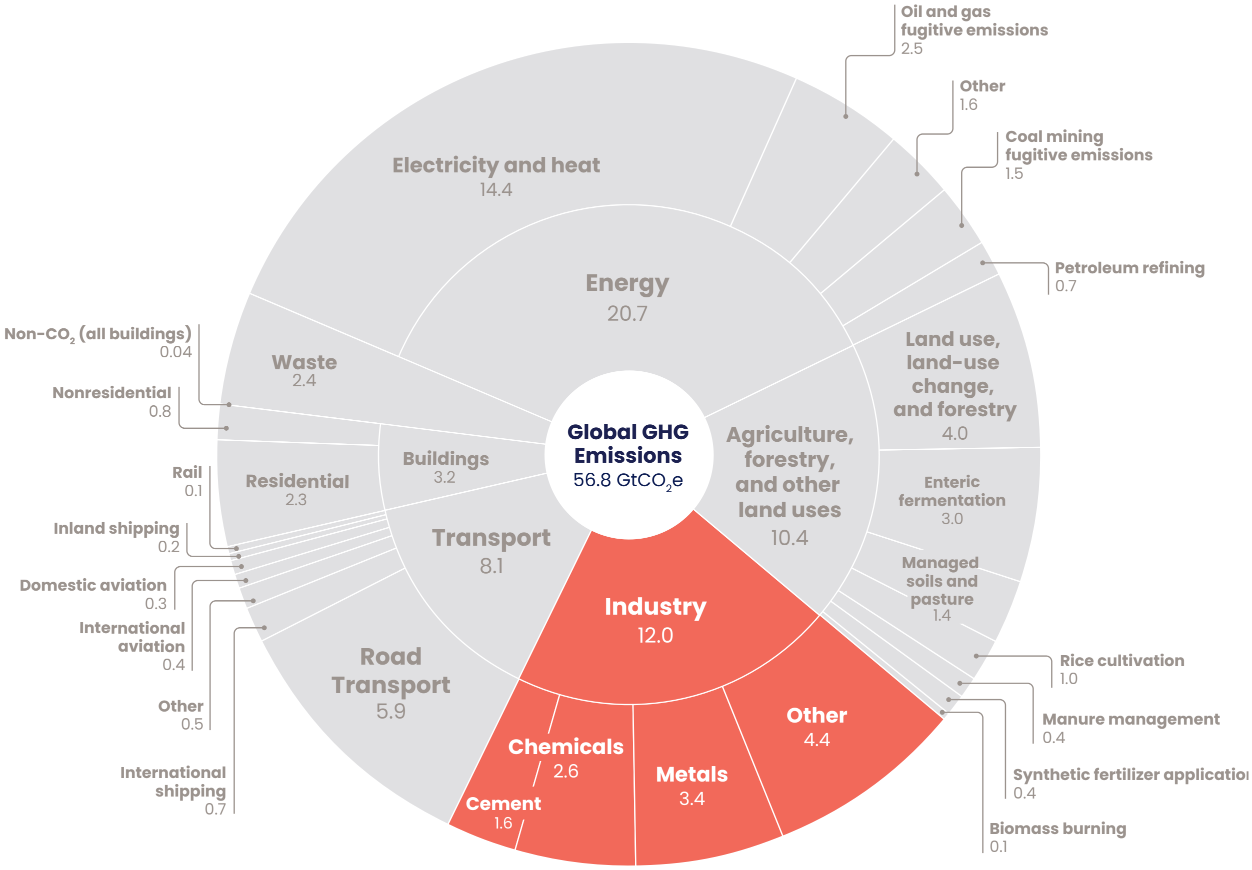
SECTION 4

Industry

Industry—a sector that encompasses the production of goods and materials like cement, steel, and chemicals, as well as the construction of buildings, roads, bridges, and other infrastructure—represents a major and growing source of GHG emissions. This encompasses both direct GHG emissions from fuel combustion and industrial processes (e.g., the chemical reactions involved in creating cement) across the industrial subsectors, as well as indirect GHG emissions from the generation of power and heat that are purchased to drive these processes. Direct GHG emissions reached 12 $GtCO_2e$ in 2021, representing roughly a fifth of global emissions (Figure 20) (Minx et al. 2021; European Commission and JRC 2022). When accounting for indirect GHG emissions, this figure rises from roughly 12 $GtCO_2e$ to 17 $GtCO_2e$ (Figure 21) (Minx et al. 2021; European Commission and JRC 2022; IEA 2022i).

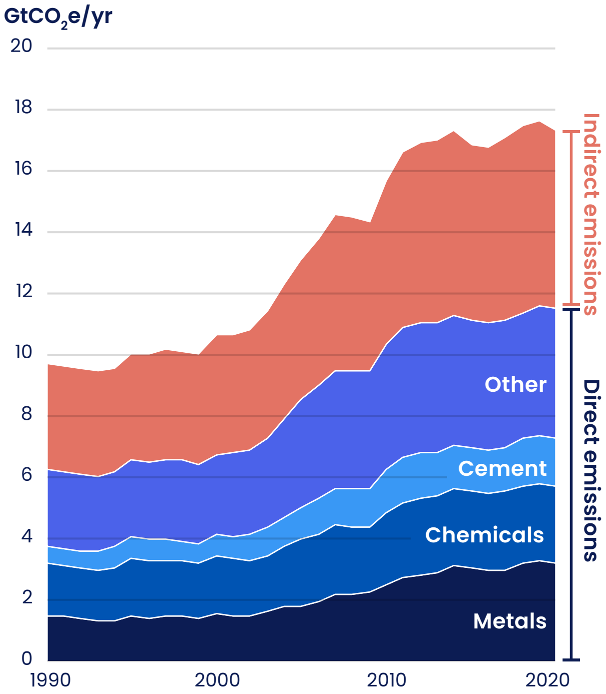
Together, both direct and indirect GHG emissions from industry have grown quickly since 2000 (Figure 21). Increasing demand for industrial products, driven by rising income, population growth, urbanization, and infrastructure development, has fueled significant growth in the extraction and production of materials around the world. Indeed, industrial expansion accounted for about 45 percent of worldwide growth in GHG emissions over the last two decades (Lamb et al. 2021; IPCC 2022b). Annual growth in industrial GHG emissions has mirrored periods of global economic expansion (until 2008) and recession and recovery (Minx et al. 2021). It slowed from 4 percent between 2000 and 2010 to 1.8 percent between 2011 and 2020. Moreover, in 2020, CO_2 emissions from the industry sector fell by another 179 million tonnes as governments around the world adopted measures to reduce the spread of COVID-19 (Sikarwar et al. 2021). New data indicate that industry emissions have rebounded, increasing by 5.7 percent in 2021, with growth slowing to about 1.1 percent in 2022 (Liu et al. 2023). Decarbonizing industry, then, must play a role in limiting warming to 1.5°C.

FIGURE 20 | Industry's contribution to global net anthropogenic GHG emissions in 2021



Notes: CO_2 = carbon dioxide; GHG = greenhouse gas; $GtCO_2e$ = gigatonnes of carbon dioxide equivalent.
Sources: Minx et al. (2021); European Commission and JRC (2022).

FIGURE 21 | Global direct and indirect GHG emissions from industry



Notes: GHG = greenhouse gas; $GtCO_2e/yr$ = gigatonnes of carbon dioxide equivalent per year. The data exclude GHG emissions from waste management (except from circularity such as production of scrap in steelmaking). "Other" includes a range of manufacturing processes, such as those for pulp and paper, food and tobacco, and glass and ceramics. Finally, Minx et al. (2021) and European Commission and JRC (2022) provide an estimate of direct and indirect GHG emissions from industry through 2020. Data on indirect GHG emissions from industry, specifically, are not yet available for 2021. But because they represent such a significant share of this sector's total emissions (34% in 2020), this figure includes indirect GHG emissions and excludes data from 2021.

Sources: Minx et al. (2021); European Commission and JRC (2022); IEA (2022i).

Global assessment of progress for industry

Transforming industry to achieve these deep GHG emissions reductions is possible, but it will require significant interventions, as well as the participation of a wide range of actors, across the sector.

Reducing demand for industrial products through avoiding overconsumption, material substitution, material efficiency, and increased circularity will be essential to make net-zero emissions more attainable in the industry sector. Such efforts can also help minimize the other harmful impacts to people and the environment caused by industrial products, such as hazardous chemicals and plastics. Improving energy efficiency can help reduce GHG emissions by cutting overall energy use. It can also reduce the total amount of energy that otherwise would need to be decarbonized through other means. Electrification with a zero-carbon power supply offers another strategy for curbing releases of GHGs, particularly for low- and medium-heat processes that currently rely on fossil fuels. However, not all industrial processes can be easily electrified. Decarbonizing industry will require additional solutions, such as switching to new zero-carbon fuels to deliver high heat, developing technologies that do not depend on high heat or can achieve it through electrification, and eliminating or capturing process emissions—those emissions from chemical reactions inherent to production processes, not from fossil fuel combustion—to the greatest extent possible. Combining conventional technologies with carbon capture, utilization, and/or storage (CCU/S) will therefore also play a critical role in the decarbonization of industry.

Alternatives to generating heat from fossil fuels to run industrial processes are beginning to emerge. Monitoring the share of electricity in industry, specifically, helps track progress toward independence from fossil fuels as the source of heat for industrial processes. Changes in the carbon intensity of cement and steel production over time reflects improvements in energy efficiency, progress in electrification, and adoption of low-carbon technologies for processes that cannot be electrified.[24] The development and deployment of new technologies is key given the inherent process emissions in conventional cement-making and the significant reliance on coke—a material derived from coal—during steel manufacturing. Together, cement and steel are responsible for about 40 percent of direct GHG emissions from industry, and the decarbonization of these sectors is beginning to get more attention (Deloitte 2021). Production of green hydrogen is also tracked in this report, as it is critical to the decarbonization of steel and other industries. The need for and status of these efforts are detailed below and summarized in Table 3. It is important to note that, while other industries such as food and beverages, glass, and aluminum are not tracked in this report, addressing emissions from those industries is needed to fully decarbonize the sector.

TABLE 3 | Summary of global progress toward industry targets

INDICATOR	MOST RECENT DATA POINT (YEAR)	2030 TARGET	2035 TARGET	2050 TARGET	LIKELIHOOD OF FOLLOWING AN S-CURVE	ACCELERATION FACTOR	STATUS
Share of electricity in the industry sector's final energy demand (%)	29 (2021)[a]	35–43	51–54 (2040)	60–69	↗	4x	✕
Carbon intensity of global cement production (kgCO$_2$/t cement)	660 (2020)[b]	360–70[b]	N/A	55–90[b]	↗	>10x	✕
Carbon intensity of global steel production (kgCO$_2$/t crude steel)[c]	1,890 (2020)[b,d]	1,340–50[b]	N/A	0–130[b]	↗	N/A; U-turn needed	⮌
Green hydrogen production (Mt)	0.027 (2021)	58[e]	N/A	330[e]	⤴	N/A; author judgment[f]	✕

Notes: kgCO$_2$/t = kilograms of carbon dioxide per tonne; Mt = million tonnes. See Jaeger et al. (2023) for more information on methods for selecting targets, indicators, and datasets, as well as our approach for assessing progress.

[a] Historical data from IEA (2023l) accessed with a paid license to the IEA's datasets.

[b] Targets and historical emissions data include direct and indirect GHG emissions.

[c] The carbon intensity of steel production accounts for both primary and secondary steel.

[d] The 2021 data point from the World Steel Association is excluded due to a change in the methodology to derive the data.

[e] The targets refer to what is needed for the whole economy to decarbonize and thus not only for the industry sector.

[f] For indicators categorized as S-curve likely, acceleration factors calculated using a linear trendline are not presented, as they would not accurately reflect an S-curve trajectory. The category of progress was determined based on author judgment, using multiple lines of evidence. See Appendix C and Jaeger et al. (2023) for more information.

Sources: Historical data from IEA (2023l); GCCA (2023); WSA (2022); and IEA (2022l); targets from CAT (2020b, 2023a); and IEA (2022t).

Electrify industry

The industrial sector consumes 37 percent of all final energy use (i.e., energy consumed by end-use sectors such as industry, transport, and buildings), with heat accounting for two-thirds of industrial energy demand (IEA 2022m; Bellevrat and West 2018). Besides using energy to provide heat, industry uses it to operate motors and machinery, and as industrial feedstock (carbon-based raw material used to make products). Electrifying industry means using electricity, rather than carbon-intensive fossil fuels, to run motors and machinery and to provide heat. Replacing fossil fuels with zero-carbon electricity to generate heat will thus reduce the emissions intensity of industrial production.

Historically, industrial companies have focused on electrifying industrial operations that do not involve heat, including machinery like pumps, robotic arms, and conveyor belts. These efforts have helped the global rate of electrification to grow at a steady pace in recent years, but there is room to electrify a wider range of industrial processes involving heat in the near term (e.g., drying, evaporation, distillation, etc.) (Roelofsen et al. 2020; Bellevrat and West 2018). Different industrial processes require heat at different temperatures, and about half of industrial heat demand is for high-temperature heat, at 400°C or above. The other half is evenly split between medium-temperature heat (100–400°C), needed to manufacture items like plastics, textiles, and paper, and low-temperature heat (below 100°C), needed for food and beverage processing and mining (IEA 2017b). Many technologies that can increase electrification of low- and medium-heat processes are already commercialized and readily available for adoption (Roelofsen et al. 2020; Bellevrat and West 2018). However, barriers to industrial electrification include the high capital costs, the price of electricity relative to that of heating fuels, process- and temperature-specific synergies and customizations that limit the ability to mass produce equipment for electrification, a lack of policy support, and the long lifetime of existing capital investments relying on heat from fossil fuels (Thiel and Stark 2021; IEA 2022s; Bellevrat and West 2018).

INDUSTRY INDICATOR 1:

Share of electricity in the industry sector's final energy demand (%)

- **Targets:** The share of electricity in the industry sector's final energy demand increases to 35–43 percent by 2030, 51–54 percent by 2040, and 60–69 percent by 2050.

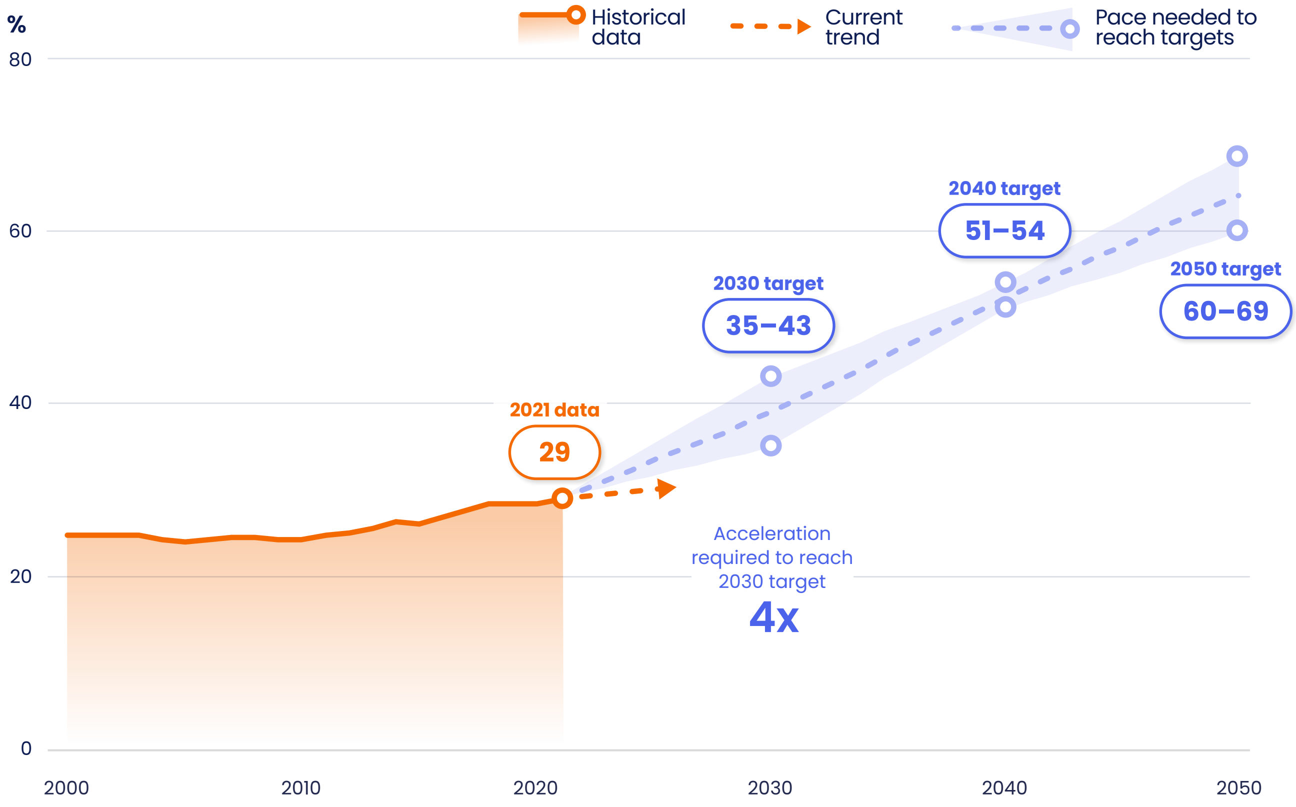
The share of electricity in the industry sector rose from about 28 percent of the sector's final energy demand to 29 percent from 2017 to 2021. Its average annual growth rate during this period was 1.6 percent. Although this rate of change is heading in the right direction, it is well off track and needs to accelerate fourfold to reach the 1.5°C-aligned near-term target for 2030.

Narrowing the difference in operational costs between providing heat with electricity and with fossil fuels—through tax exemptions and cross subsidies—is critical to making the electrification of heat economical. While broader solutions such as carbon pricing and declining prices of electricity will support electrification (see below), the diverse range of industrial processes and products across several subsectors, with their specific requirements for temperatures, will require customized technological solutions (Deason et al. 2018). Policy support is needed for direct electrification using technologies such as industrial heat pumps—which extract and transfer heat from the pump's surroundings rather than generating it and are significantly more efficient than combustion technologies—to provide low-temperature heat in industries such as paper, food, and chemicals.

Efforts to electrify industry can bring new benefits to communities. Replacing fossil fuel combustion in industrial plants with electricity can reduce local air pollution and associated health impacts. Industrial electrification policies should ensure that facilities located in minority and low-income communities—which are often disproportionately affected by industrial activities—are prioritized for electrification while also addressing other harmful impacts. This will ensure that improved air quality and health benefits are equally realized across communities (Hasanbeigi et al. 2023).

FIGURE 22 | Historical progress toward 2030, 2040, and 2050 targets for share of electricity in the industry sector's final energy demand

✕ **Right Direction, Well Off Track** **S-Curve Possible**



Notes: See Jaeger et al. (2023) for more information on methods for selecting targets, indicators, and datasets, as well as our approach for assessing progress.

Sources: Historical data from IEA (2023l), accessed with a paid license to the IEA's datasets; targets from CAT (2023a).

Industries will need qualified personnel to implement electrification technologies (IEA 2022s). This requires greater investment in education and workforce certification and training programs—such as on installation, operation, and maintenance of industrial heat pumps—as well as training opportunities accessible to low-income and underserved communities (Hasanbeigi et al. 2023; IEA 2022s). Over time, a pool of skilled professionals can be developed as new jobs are created to integrate electrification technologies in industry.

To reduce emissions, industrial processes must be electrified with zero-carbon electricity, either grid or off-grid. As industrial demand for zero-carbon electricity grows, policies must facilitate additional deployment of clean electricity to meet the growing needs of both industry and populations already struggling with frequent blackouts and rising electricity costs (Tobias and Makoma 2023). Further, planning decisions related to the location of new power plants and transmission and distribution lines should consider their impact on communities (see Power section) (Hasanbeigi et al. 2023).

Commercialize new solutions for cement and steel

For high-temperature processes that cannot be electrified, zero-carbon fuels or shifts to new technologies that do not require high temperatures will be required, as will developing new technologies and zero-carbon feedstocks to reduce industry's nonenergy-related emissions from chemical processes (i.e., process emissions). For example, shifting primary steel production from blast furnaces to green hydrogen–based steel production can eliminate process emissions from the consumption of coal, and reduce the need for high temperatures. Accelerating this shift across industries such as cement and steel will prove especially critical, not because the technologies do not exist but rather because the decarbonization of the industry sector started significantly later than other sectors. Major barriers to the commercialization of new solutions for reducing process emissions and emissions from high-temperature heat include a lack of demand for near-zero carbon industrial products; inadequate policy and regulations, research and development, and access to finance; and high upfront capital costs (Boehm et al. 2022).

INDUSTRY INDICATOR 2:

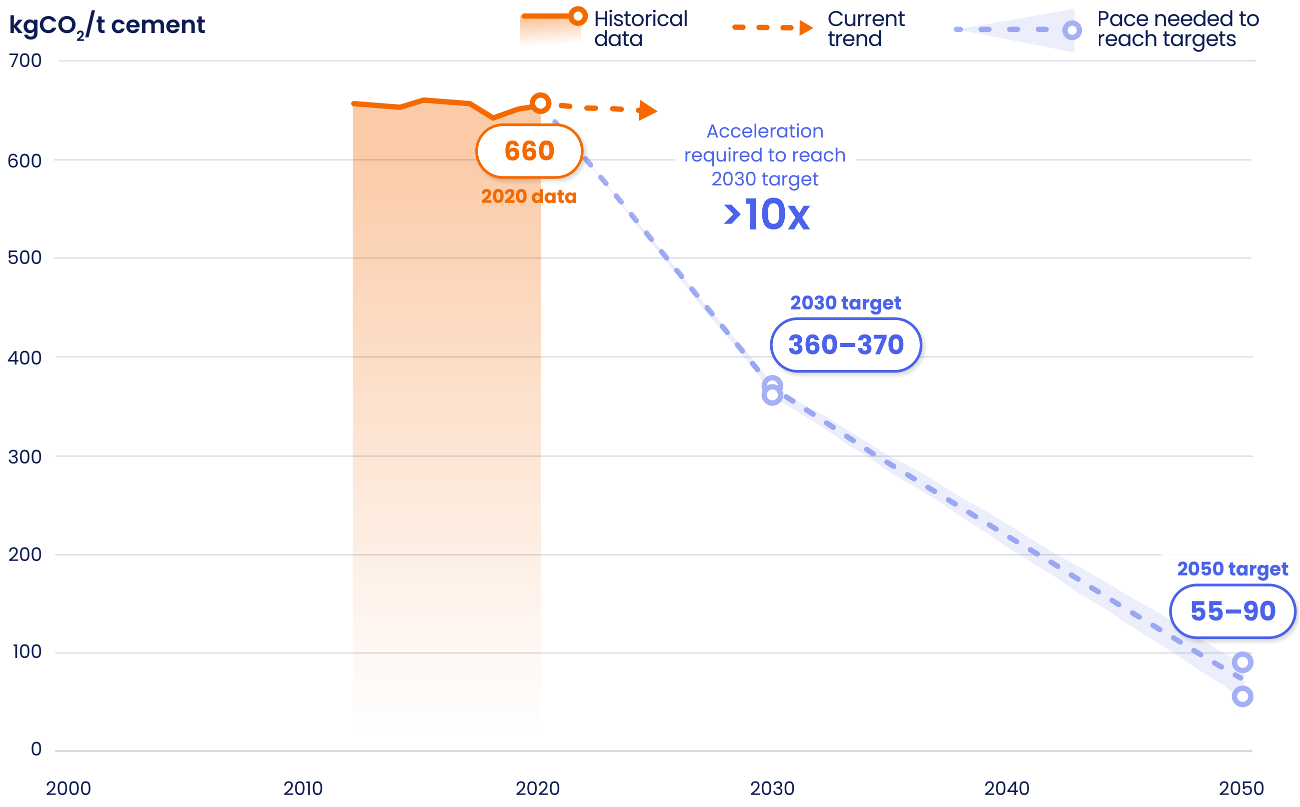
Carbon intensity of global cement production (kgCO_2/t cement)

Targets: The carbon intensity of global cement production declines to 360–70 kilograms of carbon dioxide per tonne (kgCO_2/t) of cement by 2030 and 55–90 kgCO_2/t of cement by 2050, with an aspirational target to achieve 0 kgCO_2/t of cement by 2050.[25]

Notably, while total CO_2 emissions from global cement production increased in recent decades, its carbon intensity decreased, due primarily to efficiency improvements. However, these declines have leveled off in recent years as the energy efficiency improvements have neared the limit of what is technologically possible. Reductions in the clinker-to-cement ratio, with clinker being the "glue" that binds the raw materials of cement together, can lower the emissions intensity in the short term. Using novel materials and methods, about 40–50 percent of cement emissions could be avoided through clinker substitution (IPCC 2022b). In the last 10 years, the global average clinker-to-cement ratio has fluctuated between 75 and 78 percent, and is one of the main drivers of change in cement emissions intensity (GCCA 2023). While the average trend over the last five years is decreasing, the rate of change is well off track to meet the 2030 target (Figure 23). To meet the target, the current rate of change needs to accelerate by a factor of more than 10.

FIGURE 23 | Historical progress toward 2030 and 2050 targets for carbon intensity of global cement production

☒ **Right Direction, Well Off Track** **S-Curve Possible**



Note: $kgCO_2/t$ = kilograms of carbon dioxide per tonne. Targets and historical emissions data include direct and indirect emissions. See Jaeger et al. (2023) for more information on methods for selecting targets, indicators, and datasets, as well as our approach for assessing progress.

Sources: Historical data derived by authors using data from GCCA (2023); targets from CAT (2020b).

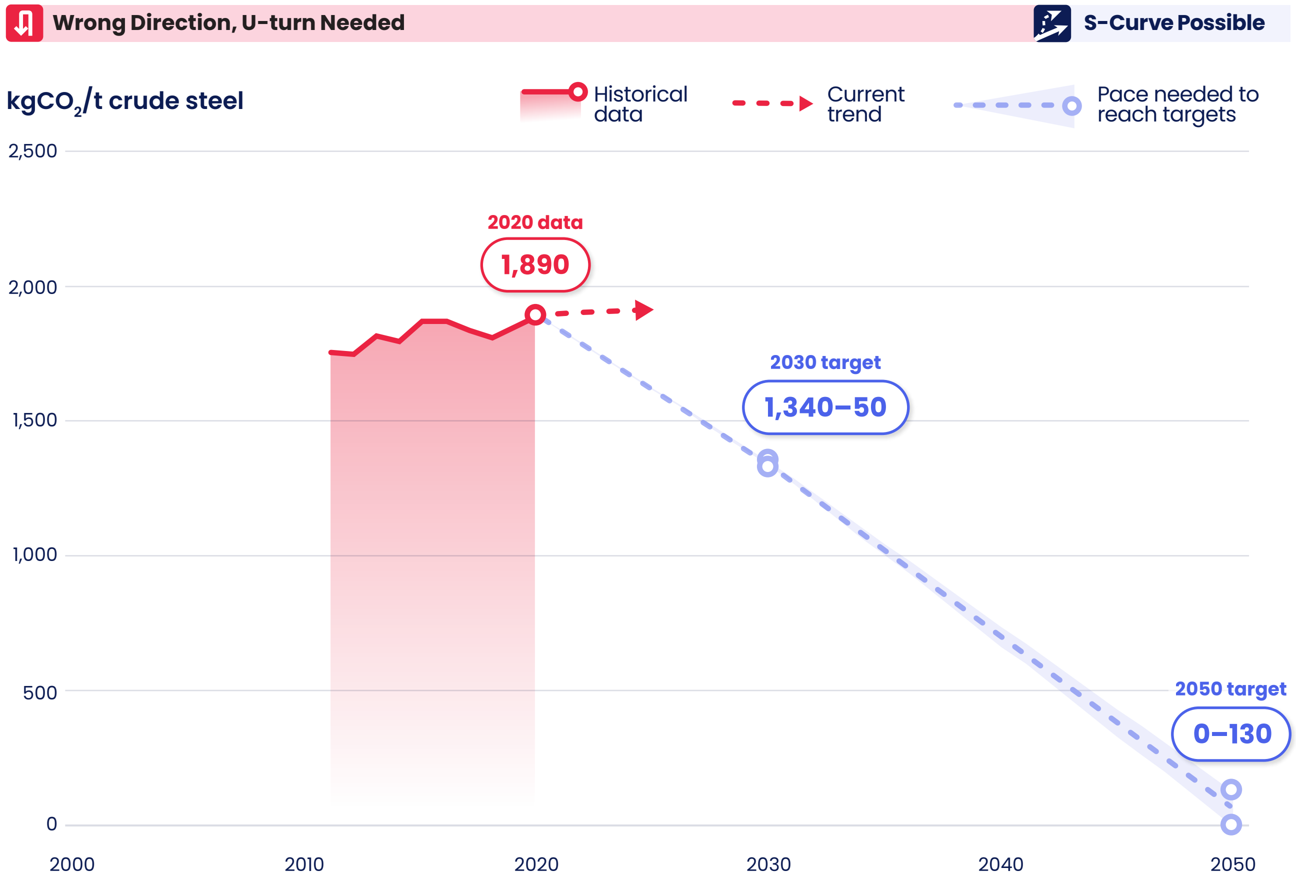
INDUSTRY INDICATOR 3:
Carbon intensity of global steel production ($kgCO_2/t$ crude steel)

- **Targets:** The carbon intensity of global steel production declines to 1,340–50 kilograms of carbon dioxide per tonne ($kgCO_2/t$) of crude steel by 2030 and 0–130 $kgCO_2/t$ of crude steel by 2050.[26]

Overall, the carbon intensity of global steel production has remained largely stable over the past decade,[27] although the last five years have witnessed a slight increase, meaning that the indicator is moving in the wrong direction to meet the 2030 and 2050 targets (Figure 24).[28] Since last year's report, the World Steel Association (WSA) has updated its methodology to calculate the carbon intensity of steel production, which results in slightly higher figures (WSA 2023). To avoid mixing data resulting from different methodologies, this year's report does not provide any updated information and relies on the same data as the 2022 report (WSA 2022). The status of the indicator is thus not updated and is going in the wrong direction.

Primary steelmaking involves the reduction of iron ore into pig iron, which is further processed into steel, while secondary steelmaking involves recycling and processing of scrap steel, which is done in an electric arc furnace (EAF) that runs on electricity. Changing the trajectory of steel sector emissions intensity will require an increase in secondary steel production, and a far greater share of primary steel production will need to rely on new technologies. These include the green hydrogen–based direct reduced iron to electric arc furnace (H2 DRI-EAF), using DRI with the submerged arc furnace (SAF) to replace the blast furnace and using existing the basic oxygen furnace (DRI-SAF-BOF), iron ore electrolysis, and carbon capture and usage or storage (CCU/S) (IEA 2021b; Nicholas and Basirat 2022).[29] It is important to note that not all of these technologies are near-zero compatible. Carbon capture on blast

FIGURE 24 | Historical progress toward 2030 and 2050 targets for carbon intensity of global steel production



Note: kgCO$_2$/t = kilograms of carbon dioxide per tonne. Targets and historical emissions data include direct and indirect GHG emissions, and the carbon intensity of steel production accounts for both primary and secondary steel. The 2021 data point from the World Steel Association is excluded due to a change in the methodology to derive the data. See Jaeger et al. (2023) for more information on methods for selecting targets, indicators, and datasets, as well as our approach for assessing progress.

Sources: Historical data from WSA (2022); targets from CAT (2020b).

furnaces, for instance, is not compatible with near-zero, while some options for carbon capture on DRI could be. Achieving net-zero emissions through carbon capture on blast furnaces will require addressing residual emissions, as it does not capture 100 percent of CO$_2$ emissions. The suitability of carbon capture and storage (CCS) also depends on the availability of suitable sites in proximity to CO$_2$ storage locations. For carbon capture and utilization (CCU) to be considered carbon-neutral, the captured carbon must be used in materials where the carbon is not released into the atmosphere. The role of these different technologies varies across different studies, but there is an increasing consensus on the limited role carbon capture will have in a Paris-compatible scenario for the steel sector, while the role for green hydrogen–based steel has strongly increased compared to that in older studies (Agora Industry and Wuppertal Institute 2023; MPP 2022b).

Secondary steelmaking is the least energy-intensive way to produce steel and can be decarbonized by ensuring that the power supply is zero-carbon. While secondary steelmaking could be ramped up, there will not be enough scrap steel to satisfy the full demand for steel in the foreseeable future. Therefore, primary steelmaking will still be needed, and methods to decarbonize it will need to be developed. Today, most primary steel is produced using blast furnaces (BF), which inherently rely on coal. The only way to significantly reduce emissions from this production route is through CCU/S, which has not yet been proven at scale. In contrast, the DRI route can use hydrogen instead of fossil fuels and is thus not reliant on CCU/S as the only decarbonization alternative.[30]

INDUSTRY INDICATOR 4:

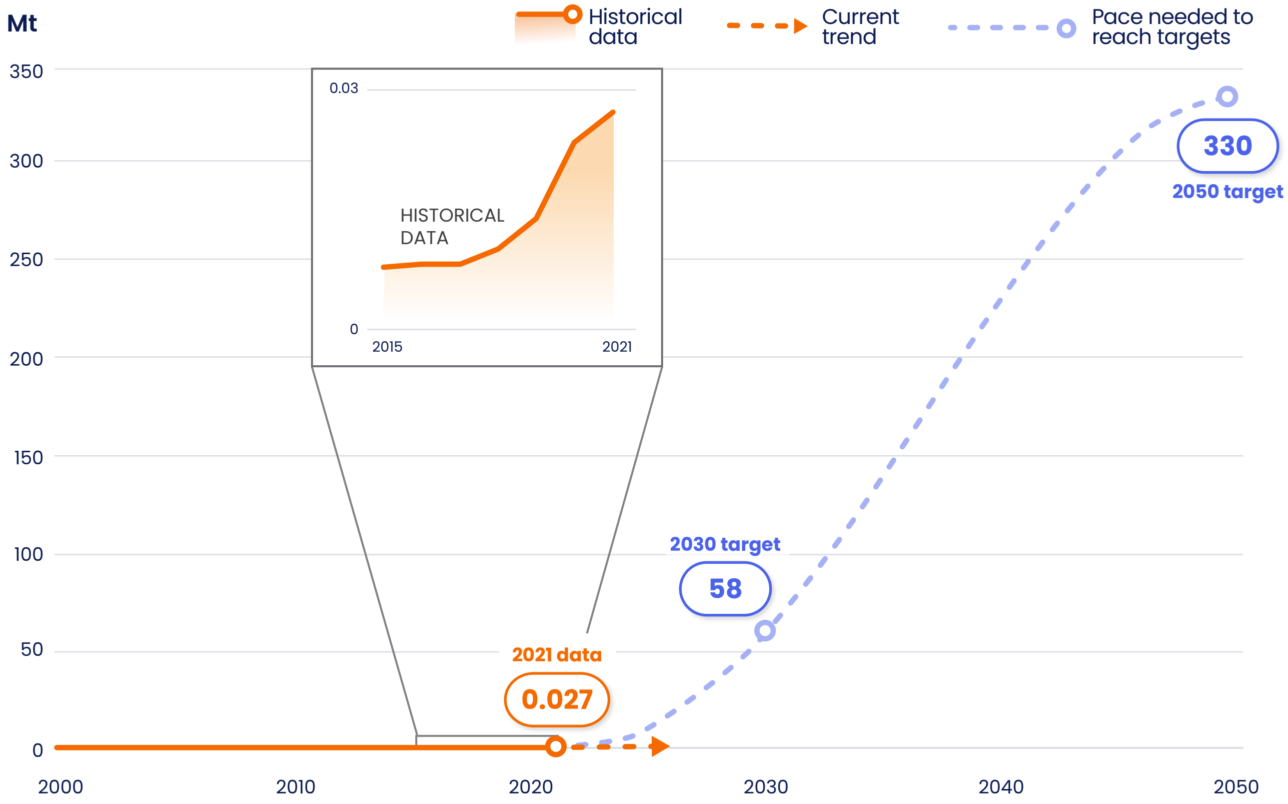
Green hydrogen production (Mt)

- **Targets:** Green hydrogen production capacity reaches 58 million tonnes (Mt) by 2030 and 330 Mt by 2050.

Electrifying high-temperature processes is challenging, and many industries also rely on carbon-based feedstocks. Direct electrification coupled with zero-carbon electricity cannot overcome all of these challenges. Instead, green hydrogen—produced with zero-carbon electricity by splitting water into hydrogen and oxygen by an electrolyzer—can be used both to generate high-temperature heat and as a feedstock directly, or it can produce feedstocks used in industry. For the production of clean feedstocks, such as synthetic petrochemicals, carbon captured from the atmosphere using direct air capture is needed in addition to green hydrogen. These decarbonized feedstocks have their own suite of health and environmental risks and should only be used to transition to products that are not toxic. In addition to an increased demand for green hydrogen resulting from the application of new technologies such as hydrogen-based DRI steelmaking, existing hydrogen production from fossil fuels also needs to be replaced with green and zero-carbon hydrogen. The phase-out of fossil fuel production, such as oil refining that uses methanol, will also reduce the existing demand for hydrogen. As an emerging technology, green hydrogen cannot yet meet global demand for hydrogen,[31] particularly in industry. Green hydrogen accounted for just 0.03 percent (0.027 Mt) of hydrogen production in 2021 based on data from the IEA's Hydrogen Projects Database (IEA 2022l).

FIGURE 25 | Historical progress toward 2030 and 2050 targets for green hydrogen production

☒ **Right Direction, Well Off Track** **S-Curve Likely**



Note: Mt = million tonnes. The targets refer to what is needed for the whole economy to decarbonize and thus not only for the industry sector. Also, for indicators categorized as S-curve likely, acceleration factors calculated using a linear trendline are not presented, as they would not accurately reflect an S-curve trajectory. The category of progress was determined based on author judgment, using multiple lines of evidence. More specifically, this indicator is categorized as well off track, because it is a new technology that is still in the emergence stage of an S-curve. The current trend arrow assumes that the current rate of exponential growth in green hydrogen continues along an S-curve, but because green hydrogen production is at such a low starting point today, even exponential growth appears flat. See Appendix C and Jaeger et al. (2023) for more information on methods for selecting targets, indicators, and datasets, as well as our approach for assessing progress.

Sources: Historical data from IEA (2022l); targets from IEA (2022t).

Transitioning to a 1.5°C pathway will require green hydrogen use to grow rapidly, reaching 58 Mt in 2030 and 329 Mt in 2050 (Figure 25). With supportive policies, such as carbon pricing or public procurement of low-carbon industrial products, green hydrogen capacity could increase rapidly and nonlinearly, with adoption rates following an S-curve trajectory of change. However, this technology is relatively nascent and remains in the emergence phase of an S-curve, so global progress toward this near-term target remains well off track. Green hydrogen production increased 38 percent per year on average over the past five years, but it is starting from such a low level that even if exponential growth continues at this rate, production still would not reach even 1 Mt by 2030.

Recent developments across industry

Several advances have been made in the past year with regards to policy-, technology-, and investment-related enablers to commercialize industrial decarbonization. Carbon pricing can be an important and powerful instrument to incentivize the adoption of novel low-carbon technologies. Though there was no significant increase in global GHG emissions covered by carbon pricing systems since 2021, India, with one of the world's fastest-growing industrial sectors, released the draft framework for a carbon market scheme in March 2023 (Ghosh 2023; World Bank 2023d). This carbon market will likely target 11 sectors, including power, aluminum, cement, petroleum refineries, and steel (Singh 2023b). In May 2023, the European Union's Carbon Border Adjustment Mechanism (CBAM) was officially adopted, and its transitional application will start in October 2023. The mechanism aims to avoid carbon leakage by setting a price on carbon for imported industrial products and will be aligned with the phase-out of free allowances under the EU emissions trading scheme (European Commission n.d.a).

New policy packages were announced in 2022 to commercialize deep emission reduction technologies by incentivizing new investments and facilitating access to finance. The U.S. government passed the Inflation Reduction Act in August 2022, which included a $6 billion grant program aimed at technology developers, industry actors, universities, and others to decarbonize heavy industry (Gardner 2023; U.S. Government 2022). The act also includes green hydrogen–related measures that could benefit industrial decarbonization efforts. It also increased the subsidy per tonne of captured CO_2 from $50 to $85 as part of an update to the existing tax credit that incentivizes industries, investors, and developers to support CCS (CATF 2022b). Such an increase can make it financially viable to capture carbon from processes with lower concentrations of CO_2 in the exhaust gas, as is the case in many industrial processes. However, the act also includes measures that could further delay industrial decarbonization. For instance, it provides $60 per tonne of captured CO_2 for enhanced oil recovery, which uses captured carbon to produce additional oil. To ensure that legislation like the Inflation Reduction Act is efficiently applied and truly supports industrial decarbonization, it is also important that robust monitoring, reporting, and verification systems for emissions by companies receiving the subsidies be in place.

Legislation like the Inflation Reduction Act can have a cascading effect, as other countries and regions bump up their own support for a low-carbon industry to avoid losing their competitive edge in global markets. For example, the European Commission (EC) released its Net-Zero Industry Act as a response to the Inflation Reduction Act in March 2023. The EC act sets targets for specific technologies considered essential for decarbonizing the European Union's economy and aims to domestically produce clean technology (such as CCU/S and electrolyzers) to meet 40 percent of the demand in 2030 (di Sario 2023). It also sets a 2030 target for 50 Mt of captured CO_2 to be injected into permanent storage sites (European Commission 2023f). To meet the target, it asks EU-based oil and gas producers to contribute to the development of captured CO_2 storage sites proportional to their oil and gas production (European Commission 2023f). This will contribute to the decarbonization of the industry sector, as CCU/S is one of the measures to achieve that (Conley and Botwright 2023).

While subsidies can advance the low-carbon transition in industry, they also risk disrupting international trade flows and leaving behind developing and emerging economies that cannot afford large subsidy programs (Conley and Botwright 2023). International climate finance and technology transfer supporting clean industries in developing countries has an important role to play in ensuring a just transition (see further discussion of equity and just transitions in Box 8). In December 2022, the G7 initiated the Climate Club to accelerate the implementation of the Paris Agreement and help resolve challenges arising from instruments such as CBAM and the Inflation Reduction Act (European Parliament 2023c). Availability of financial support can further incentivize countries from the Global South to join the club and facilitate cooperation with the Global North (Unger and Thielges 2023).

Recent developments in electrifying industry

Key recent positive developments related to electrifying industry include policies to incentivize the adoption of available technology for electrifying low-temperature heat. For example, the U.S. Inflation Reduction Act authorized over $15 billion to help manufacturers switch to heat pumps and other clean industrial heating technology (Rissman 2022). Industrial heat pumps are also increasingly popular in the European Union as they become more cost-competitive due to rising natural gas prices in the wake of Russia's invasion of Ukraine (Hockenos 2023). Europe's Net-Zero Industry Act also includes heat pumps, among other technologies, that should be promoted (HPT Magazine 2023). In 2023, Germany started a program to catalyze investments in low-carbon production technologies through targeted subsidies estimated to be around $50 billion (Segal 2023).

For high-temperature processes, such as steel and cement production, that require temperatures of more than 1,000°C, electrification is technically possible but requires further R&D, pilots, and demonstration to become economically feasible.[32] Some recent promising developments for electrifying high-temperature processes include researchers at Massachusetts Institute of Technology (MIT) carrying out pilot demonstrations to produce cement using electricity at low temperatures; a patent awarded to SaltX in March 2023 for electric arc calciner technology, which uses zero-carbon electricity to produce cement but at very high temperature, with a demonstration plant expected to be built this year; and Boston Metal's development of molten oxide

BOX 8 | Equity and just transition in the industry sector

The decarbonization of the industry sector will come with challenges related to equity and just transitions. The production of many industrial products requires mining of raw materials such as iron ore for steelmaking and limestone for cement-making. An increased demand for iron ore to meet rising primary steel demand risks increasing the human and environmental burden. Environmental and human rights abuses have been reported in regions and communities surrounding large iron ore mining operations (e.g., miners' exposure to unsafe and unhealthy working conditions, labor and agrarian conflicts, local and Indigenous communities losing their homes, livelihoods, and access to clean air and water) (FIDH 2022). Although iron ore mining activities may slow down with higher rates of secondary steelmaking and reduced demand for steel, mining activities leave an irreversible impact on local economies and communities if these activities do not follow through with due compensation or environmental rehabilitation. It is critical to ensure that environmental hazards are fully identified, prevented, and remedied, and that affected workers and families receive just compensation for resettlement costs.

Locating or relocating industrial plants that require large amounts of zero-carbon energy to decarbonize or require green hydrogen to areas rich in renewable energy resources can help ensure that they will be economically viable. Relocation can introduce a range of justice-related implications. It can burden some regions disproportionately, strand assets, cause unemployment, have environmental implications related to the availability of freshwater and land-use requirements, and require relocation of jobs and families, reskilling of workers, and re-siting of other infrastructure (Vogl et al. 2019; Swennenhuis et al. 2022). In the steel sector, splitting ironmaking from steelmaking and moving the energy-intensive ironmaking to locations with rich renewable resources while retaining the steelmaking at the original location could limit the number of job losses (Agora Industry and Wuppertal Institute 2023).

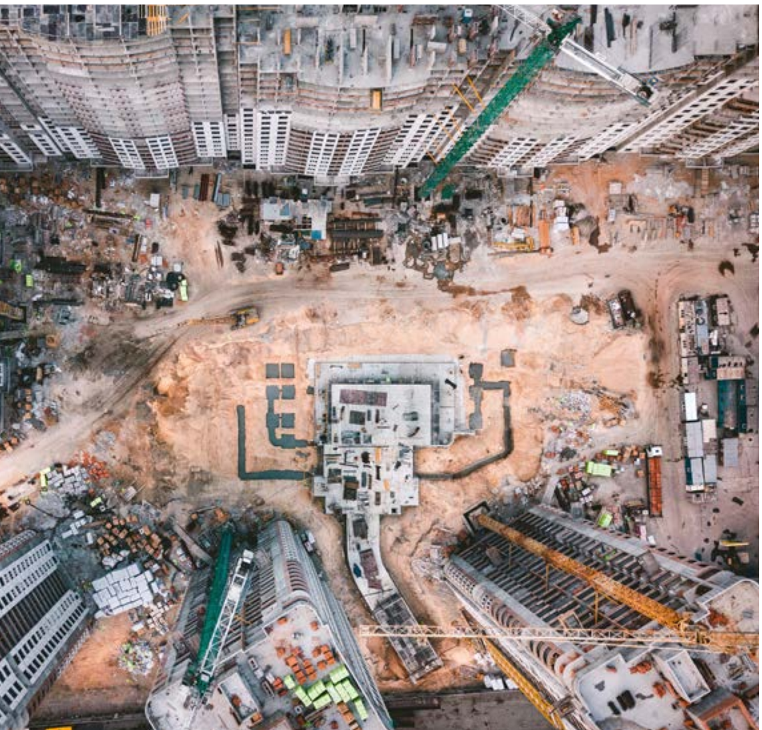
Transitioning from one kind of industry to another can also put at risk workers' gains built through years of activism by unions in some industries and need to be safeguarded. The U.S. Inflation Reduction Act, for example, includes a program to support fairly paid jobs and protect union workers' gains in energy construction jobs, but it does not extend similar protection to jobs in manufacturing industries (Swalec 2023).

electrolysis technology to produce molten iron using electricity, which has attracted investment from IFC and ArcelorMittal, the second-largest steel producer looking to decarbonize its production (Crownhart 2023; SaltX Technology 2023; Cemnet 2023a; Gleeson 2022; IFC 2023b; ArcelorMittal 2023).

Recent developments in lowering the carbon intensity of cement

There are several ways to reduce the carbon intensity of cement production (e.g., lowering the clinker-to-cement ratio by using supplementary cementitious materials [SCMs], switching to alternative materials to produce cement altogether, and applying CCU/S), with some promising developments in recent years. Achieving deep decarbonization will require further development and commercialization of new technologies, enabled by policies linked to improved incentive structures and the availability of finance.

Creating demand for low-carbon cement through measures such as public procurement and private sector purchase commitments can help derisk investments in new technologies (Lewis et al. 2023; Torres Morales et al. 2023). Canada and the United States have been leaders in this space. In December 2022, Canada announced two standards under its Green Procurement policy for embodied carbon in concrete and carbon disclosure and reduction requirements, thus imposing specific obligations on contracting authorities and vendors (O'Brien et al. 2023). In the United States, a national green procurement initiative was launched, with several states passing their own green procurement policies (Gangotra et al. 2023). Early this year, the U.S. state of New Jersey adopted a public procurement law for concrete. The law builds on the Buy Clean model spearheaded in California and now adopted by several other states. The model sets a benchmark for maximum carbon intensity of materials required in publicly funded projects. The New Jersey law has an additional tax credit for concrete producers that is even lower than the maximum carbon intensity benchmark set by the Buy Clean model (Neidl 2023).



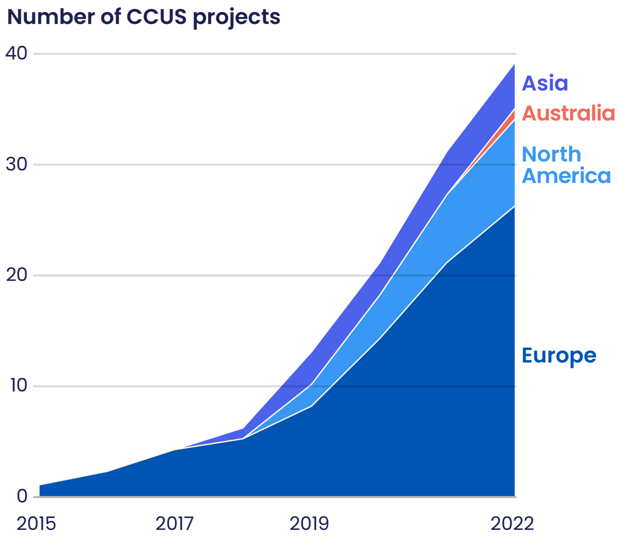
In addition to public procurement, the private sector can also support securing a demand for low-carbon cement through initiatives such as ConcreteZero and the First Movers Coalition. The Industrial Deep Decarbonization Initiative, led by the UN Industrial Development Organization, is another leading program for demand creation, which now includes the cement sector as announced at COP27 (High-Level Champions 2022b).

Cement decarbonization technologies also require adequate access to finance to counter high upfront costs, particularly in developing countries, which face growing demand for infrastructure development but have limited financial resources for low-carbon investments. In February 2023, the International Finance Corporation (IFC) and Sococim Industries, Senegal's leading cement manufacturer, announced an almost $264 million (€242 million) financing package to decarbonize Sococim's cement production (IFC 2023a).[33] It is IFC's first green loan for material manufacturing in Africa and will be used to improve energy efficiency and increase the share of alternative fuels. While cement production in Africa today only makes up a small share of global production, the demand is projected to increase rapidly with greater development and industrialization (Chen et al. 2022).

This year, the U.S. Department of Energy (DOE) awarded $3.2 million to the Solar MEAD project, which aims to fully replace fossil fuel–based heat generation for cement production with concentrated solar thermal heat (*Renewable Energy World* 2023). This could eliminate about 40 percent of direct emissions from the standard cement production process (CAT 2023a). The technology was successfully piloted at laboratory scale in 2022 by CEMEX and Synhelion, and the funding will help advance this to an industrial-scale plant.

Another important mitigation option in the cement industry is the reduction of the clinker-to-cement ratio, since clinker production is responsible for about 90–95 percent of cement emissions. Clinker can be partly replaced with supplementary cementitious materials, such as industrial wastes and clays, but the availability of industrial wastes that can be used as SCMs is declining. Using calcined clay as an SCM is promising because it can reduce process emissions by about 50 percent in the near term (Scrivener and Shell 2023).[34] Interest in calcined clay is picking up globally, with African projects clearly in the lead. Calcined clay projects have been announced in several African countries, including Ghana, Malawi, Cameroon, Côte d'Ivoire, and Egypt. Likely reasons could be the availability of raw

FIGURE 26 | Cumulative number of announced CCUS projects in the global cement sector



Note: CCUS = carbon capture utilization and storage.
Source: Lorea et al. (2022).

materials, population growth, increased industrialization and urbanization, and the chance to rely less on costly imported clinker (Cemnet 2022; Scrivener and Shell 2023; Perilli 2022). The first European plant launched operations in early 2023 in France (Cemnet 2022; Perilli 2023).

A major barrier to wider adoption of alternative cement materials is slow development and adoption of updated cement and concrete standards. Many cement and concrete standards today are prescriptive rather than performance-based and thus do not allow for the introduction of new materials. In May 2023, the Alliance for Low Carbon Cement and Concrete was launched, focusing on low-carbon cement development and calling on policymakers to improve standards, among other things (Global Cement 2023).

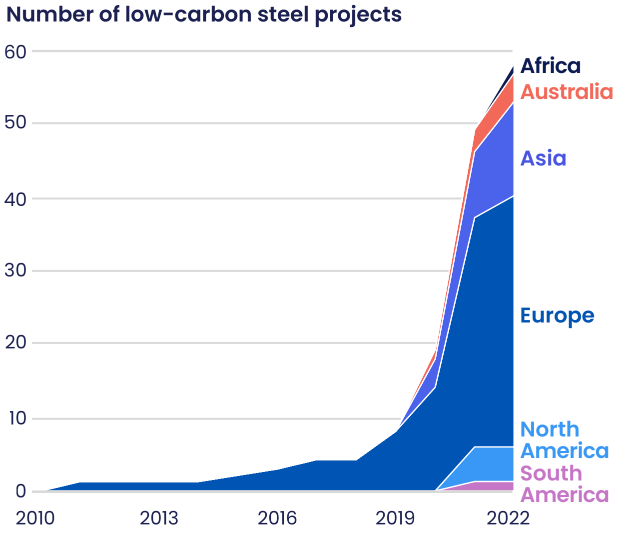
While challenges related to the development and deployment of carbon capture technology raised in this report are also relevant for cement, it is one of the few sectors where achieving near-zero emissions is likely to require a substantial build-out of CCU/S. This is reflected in the number of announced carbon capture projects in the cement sector—39 by the end of 2022—compared to 4 projects in the steel sector (Figure 26). The Norcem plant in Norway, expected to be the first CCU/S plant to become operational in the cement industry in 2024, was first shortlisted for an industrial-scale trial in 2018 (Heidelberg Materials 2023). The time required to bring a plant from the initial planning stage to full commercial operation makes the time window to achieve the Mission Possible Partnership's goal of more than 20 commerical-scale CCU/S plants operational by 2030 increasingly challenging (MPP 2022c). According to the current pipeline, only 13 full-scale plants are planned to become operational by then (Lorea et al. 2022). Further, the fact that the Global North is leading the development of CCU/S in the cement industry, while the majority of existing cement capacity is in Asia and new cement capacity is expected to be built in Asia and Africa, this creates a mismatch between where the mitigation technology is being developed and where it is needed (Chen et al. 2022). However, some recent positive developments have been observed in China—responsible for more than half of the world's annual cement production—where the largest cement CCU/S plant to date was announced in July 2023 (Cemnet 2023b).

Recent developments in lowering the carbon intensity of steel

Decarbonizing primary steelmaking will involve a combination of decarbonization technologies, all at different stages of commercialization. The understanding of how primary steel production can be decarbonized has advanced dramatically in recent years, and steel companies are increasingly publishing decarbonization targets and engaging in pilot and demonstration projects. Based on data from the Green Steel Tracker, the total number of low-carbon steel projects is increasing,[35] albeit at a significantly lower rate than in 2021 (Figure 27).[36] According to Mission Possible Partnership, about 70 low-carbon steel plants need to be operational by 2030 in order to stay on a 1.5°C-compatible pathway (MPP 2022c). The Green Steel Tracker data show that 29 full-scale plants are planned to be operational by then, signaling a strong need for accelerated deployment of low-carbon steel projects.[37] Of all announced projects, three-fourths are in Europe, North America, and Australia, with Europe accounting for almost 60 percent of them (Figure 27). While Asia has the second-largest share of projects at roughly 20 percent, South America and Africa account for just 3 percent and 2 percent, respectively.[38] This further highlights a need for increased technology transfer (Bataille et al. 2023).

Among low-carbon steel projects, the leading choice has been green hydrogen–based DRI-EAF steel production. In 2021, the first successful shipment of such steel, produced by the HYBRIT project pilot plant in Sweden, was delivered to Volvo AB, which will be the first manufacturer to produce vehicles from fossil-free steel (Vetter 2019). Such commitments, from both the private and public sectors, help to ensure demand for low-carbon steel. Between 2021 and 2022, 28 new green hydrogen–

FIGURE 27 | Number of cumulative announced low-carbon steel projects by continent



Note: Low-carbon steel technologies include low-carbon hydrogen-based direct reduced iron, scrap-based electric arc furnace, carbon capture and usage or storage, molten oxide electrolysis, biomass-based steel production, and smelting reduction.

Source: Authors' analysis of data from Green Steel Tracker (2023).

related steel projects were announced,[39] accounting for over 70 percent of the total number of low-carbon steel project announcements during this period (authors' calculations based on data from Green Steel Tracker 2023).

This emphasis on hydrogen appears likely to continue. Several major steelmakers have unveiled emission reduction or decarbonization plans largely based on the green hydrogen DRI-EAF production route. Recently, ThyssenKrupp, a major steel company globally, announced replacing blast furnaces with hydrogen-based DRI-EAF as its major carbon-neutral strategy (Bataille et al. 2023; Maddy 2023; ThyssenKrupp n.d.). Baowu, China's largest steelmaker, has set a carbon neutrality target for 2050—10 years ahead of the national carbon neutrality target (BloombergNEF 2021ba). In 2023, Baowu and Fortescue entered a memorandum of understanding to explore low-carbon steelmaking, including green hydrogen–based steelmaking (Xin 2023). The focus on hydrogen-based steelmaking is currently strongest in Europe, North America, and developed Asia, while other regions are more likely to use other technologies, such as BF with CCU/S. ArcelorMittal, the second-biggest steel producer globally, has set a target of net zero by 2050 and is also planning to shift from blast furnaces to green hydrogen–based DRI-EAF in its European and North American operations. However, the company plans to significantly expand its blast furnace capacity in India, which is now the number one country in developing new coal-based steel production globally (Nicholas and Basirat 2023; Zhi and An 2023). This reveals two substantially different approaches in different geographies. Considering the long economic lifetime of steel plants (about 40 years), building more blast furnaces as well as retrofitting existing ones heightens carbon lock-in risks (see Box 9). Increasing GHG-producing assets in one region while investing in clean assets in others also raises questions of environmental injustice. Avoiding this requires a stronger role for global standards across areas of operations.

While less advanced than hydrogen-based DRI, direct electrification of steelmaking is also attracting growing attention. In early 2023, two new projects were

BOX 9 | New research shows high risks of stranded assets resulting from new blast furnace developments

Despite pledges to lower emissions and in some places to explore new hydrogen and electricity technologies, the build-out of coal-reliant blast furnaces continues globally. Since blast furnaces are inherently reliant on coal, their decarbonization will require CCU/S. But it is becoming clearer that, while possibly suitable and needed for a limited share of global steelmaking, CCU/S will not be a viable solution for the majority of the industry. In recent years, studies have highlighted the lack of CCU/S projects compared to other decarbonization technologies, especially considering that new blast furnace capacities are still being added (de Villafranca Casas et al. 2022). According to the IEA's CCU/S projects database, only one new carbon capture project for steel was announced in 2022 (IEA 2023a). Similarly, Agora finds that only a single CCS project for coal-based steel production is planned to come online before 2030 (Agora Industry and Wuppertal Institute 2023). In addition to its slow commercialization, CCU/S technology for steelmaking comes with other externalities, such as only partial capture of CO_2 emissions, the continued release of methane emissions from coal mining, and more, which is further discussed in Jaeger et al. (2023).

A recent Paris-compatible scenario analysis by Agora even suggests that all blast furnace capacity can be phased out by 2050, thus eliminating the need for CCU/S for that technology (Witecka et al. 2023). Overall, the balance between new BF-based and DRI-based projects in the pipeline has changed in a positive direction only in the last year. An estimated 43 percent of planned projects were DRI-based and 57 percent were blast furnace–based in 2023, compared to 33 and 67 percent respectively in 2022, according to the Global Energy Monitor (Swalec and Grigsby-Schulte 2023). But this progress is far from sufficient and staying aligned with the Paris Agreement would require about 347 Mt per year of blast furnace capacity to be retired or cancelled by 2050; that is, already existing blast furnace capacity needs to be retired and planned capacity cancelled.

The countries most exposed to stranded asset risks are also the countries with the largest blast furnace steel capacity pipeline. Agora estimates that 315 Mt of additional coal-based blast furnace capacity is currently in the pipeline in emerging economies, corresponding to about 13 percent of current installed steel capacity (primary and secondary) (Agora Industry and Wuppertal Institute 2023). India currently has the largest pipeline with about 113 Mt, followed by ASEAN26 with 99 Mt, and China with 94 Mt (Agora Industry and Wuppertal Institute 2023). About 97 percent of the current blast furnace pipeline thus is led by emerging and developing countries in Asia, where demand for primary steel is rapidly growing. Along with this, existing blast furnace capacity needs to be significantly phased down. China, accounting for more than half of global steel production, out of which more than 70 percent is blast furnace–based, is home to a major part of that. As a result of the Chinese capacity swap mechanism, which requires new steel plants to be smaller than the plant being replaced, more blast furnace capacity has been retired compared to new blast furnace capacity that has been built in recent years in the country (Agora Industry and Wuppertal Institute 2023; Ranjan 2023).

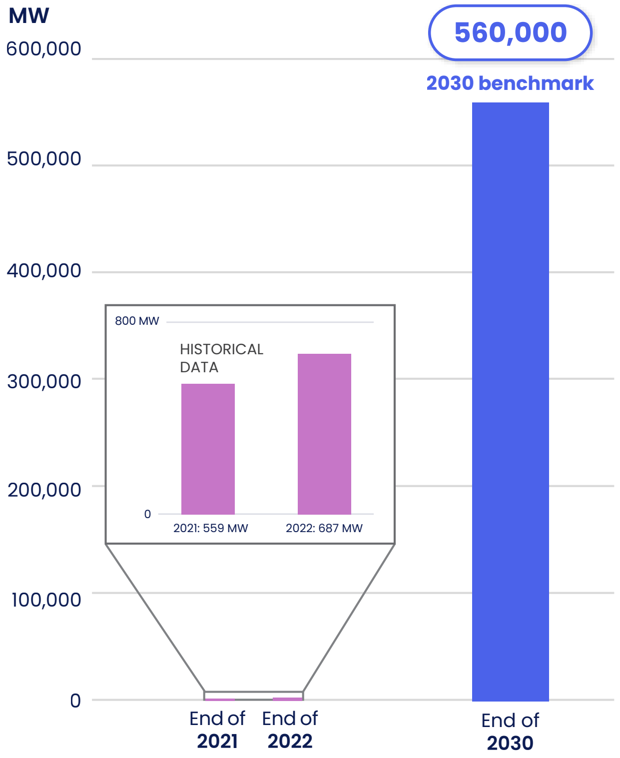
Notes: BF = blast furnace; CCS = carbon capture and storage; CCU/S = carbon capture, utilization, and/or storage; DRI = direct reduced iron; Mt = million tonnes.

announced in Australia and similar projects exist in other countries (e.g., Boston Metals and Siderwin projects in the United States and France, respectively) (Hart 2023; Vorrath 2023). Direct electrification could eliminate the need for hydrogen and, while not yet proven, may become more energy efficient.

Recent developments in green hydrogen

Green hydrogen is produced by splitting water into hydrogen and oxygen using an electrolyzer. Data on planned new electrolyzer capacity can therefore give an indication of the potential increase in green hydrogen production in the near future. According to the IEA, while global installed electrolyzer capacity grew by 23 percent from 2021 to 2022, reaching 690 MW, that level

FIGURE 28 | Globally installed electrolyzer capacity for hydrogen production



Note: MW = megawatt.
Source: IEA (2022h).

is still insufficient to power a medium-sized DRI steel plant (Vogl et al. 2018; Bhaskar et al. 2020; IEA 2023b) (Figure 28). The majority of the 70 percent increase between 2020 and 2021 came from one project in China, and, as of late 2022, about 40 percent and 30 percent of planned capacity expansion was in China and Europe, respectively.

Looking ahead, planned projects in the pipeline would amount to 134 GW in 2030, corresponding to an annual hydrogen production capacity of about 10 Mt/year.[40] That is an increase of almost 150 percent compared to the corresponding estimate based on the project pipeline in 2021; however, it is still far from sufficient to meet the 2030 target. Of the planned electrolyzer capacity, 32 percent will be in Europe, 28 percent in Australia, and 12 percent in Latin America (IEA 2022h). Electrolyzer manufacturing capacity grew from 8 GW in 2021 to 11 GW in 2022, and about 125 GW of additional capacity could be in the pipeline through 2030 (IEA 2023i).

The green hydrogen sector continues to receive political attention globally, providing a positive signal to the private sector. Between October 2021 and September 2022, 9 countries released national hydrogen strategies, bringing the total to 25 nations, as well as the European Union (IEA 2022h). In 2023, India rolled out its National Green Hydrogen Mission and allocated $36 million for the first year, with a total of $2.3 billion over seven years (Kumar 2023; Government of India 2023). Through the 2022 Inflation Reduction Act and the 2021 Infrastructure, Investment, and Jobs Act, the United States has channeled $9.5 billion in funding for hydrogen (over 80 percent being for hydrogen hubs) and has introduced production tax credits for clean hydrogen (Krupnick and Bergman 2022). It also released its draft National Clean Hydrogen Strategy and Roadmap in 2022 (U.S. DOE 2022a). Australia plans to support domestic manufacturing and boost investment in hydrogen electrolyzers through the National Reconstruction Fund passed in 2023 (Singh 2023a). China, which produces 30 percent of global hydrogen supply, released a Hydrogen Industry Development Plan in 2022 and set short-term targets (IEA 2022h).[41] Chile, which published its national green hydrogen strategy in 2020, recently secured a $150 million World Bank loan to promote investment in domestic green hydrogen projects aiming to support local communities (World Bank 2023b).

The Russian invasion of Ukraine in February 2022 is driving countries—particularly those in Europe dependent on Russian gas—to become more ambitious with regard to green hydrogen development and usage. An increasing number of countries also seek to achieve greater energy security, partly through the development of domestic green hydrogen production. The European Commission's REPowerEU plan published in May 2022 (after the EU hydrogen strategy) aims to eliminate the European Union's dependence on Russian fossil fuels before 2030. It includes hydrogen targets that are more ambitious than those in the EU hydrogen strategy, as well as a nonbinding target to import 10 million tonnes of green hydrogen by 2030. The European Hydrogen Bank was also established to boost renewable hydrogen production and imports (European Commission 2023e).

The European Union has also been particularly active in establishing international partnerships for green hydrogen imports. For example, an agreement between the European Union and Egypt was signed in 2022 for a strategic green hydrogen partnership (European Commission 2022d). The African Green Hydrogen Alliance, currently made up of Egypt, Kenya, Mauritania, Morocco, Namibia, and South Africa, was also launched in 2022 to develop green hydrogen–related projects in Africa (Green Hydrogen Organisation and Race to Zero n.d.). Other similar alliances include H2LAC, with a focus on Latin America and the Caribbean; the India Hydrogen Alliance; the Japan Hydrogen Association; and the Middle East North Africa Hydrogen Alliance. To what extent such partnerships contribute positively to exporting countries' development and support their decarbonization too will depend on the design of the partnerships and the local circumstances (Box 10).

BOX 10 | Potential risks and benefits of a global green hydrogen trade to sustainable development in the Global South

Industries such as steel may need to relocate to regions where it is cheaper to produce green hydrogen to avoid importing hydrogen for their decarbonization goals, since hydrogen is expensive to transport. But political or strategic reasons may dictate that steel industry and associated jobs are retained domestically and hydrogen needs are met through imports. However, the hydrogen-exporting country may risk jeopardizing domestic decarbonization unless adequate safeguards are ensured. While scaling up renewable energy capacity for producing green hydrogen could drive local knowledge, market development, and uptake of renewable energy elsewhere in the country, there is also a risk that efforts to build renewables remain limited to green hydrogen plants meant for export, or even pull resources away from decarbonizing the domestic energy system (Fekete and Outlaw 2023).

Uncertainties in determining the long-term global need for green hydrogen mean that investments in its large-scale production carry significant financial risks. For countries in the Global South, borrowing money for capital-intensive investments could increase debt. But these investments could be used to drive down the cost of wind and solar, decarbonize power generation, and support local value creation through hydrogen export industry—a trend already emerging in Oman (*Mining Technology* 2022; Klevstrand 2023).

Green hydrogen export projects should prioritize countries' basic development needs. For instance, universal access to electricity remains unachieved among many sub-Saharan populations. In countries with an electricity supply deficit, green hydrogen trade and mechanisms for exporting clean energy should also benefit local communities through improved access to electricity. In Namibia, with a 56 percent electricity access rate in 2020, the government is developing with a German venture a green hydrogen export project expected to generate excess electricity that can be used to improve domestic access to electricity (World Bank 2021b; Elston 2022). Standards should be developed to hold investors and governments accountable in this regard. Power Shift Africa, a Kenya-based think tank, has suggested a set of such standards to ensure that energy for green hydrogen projects is additional (Adow et al. 2022).

With adequate safeguards in place, green hydrogen development can benefit local communities by enhancing local value chains and spurring local renewable energy deployment. Supporting the development of upstream and downstream components along the green hydrogen production value chain locally can generate jobs domestically and better support local communities. Including stakeholders from all parts of society (the private sector, investors, academia, civil society, and local communities) in planning and decision-making can bring such issues to the fore and help negotiate outcomes that do not shortchange local communities.

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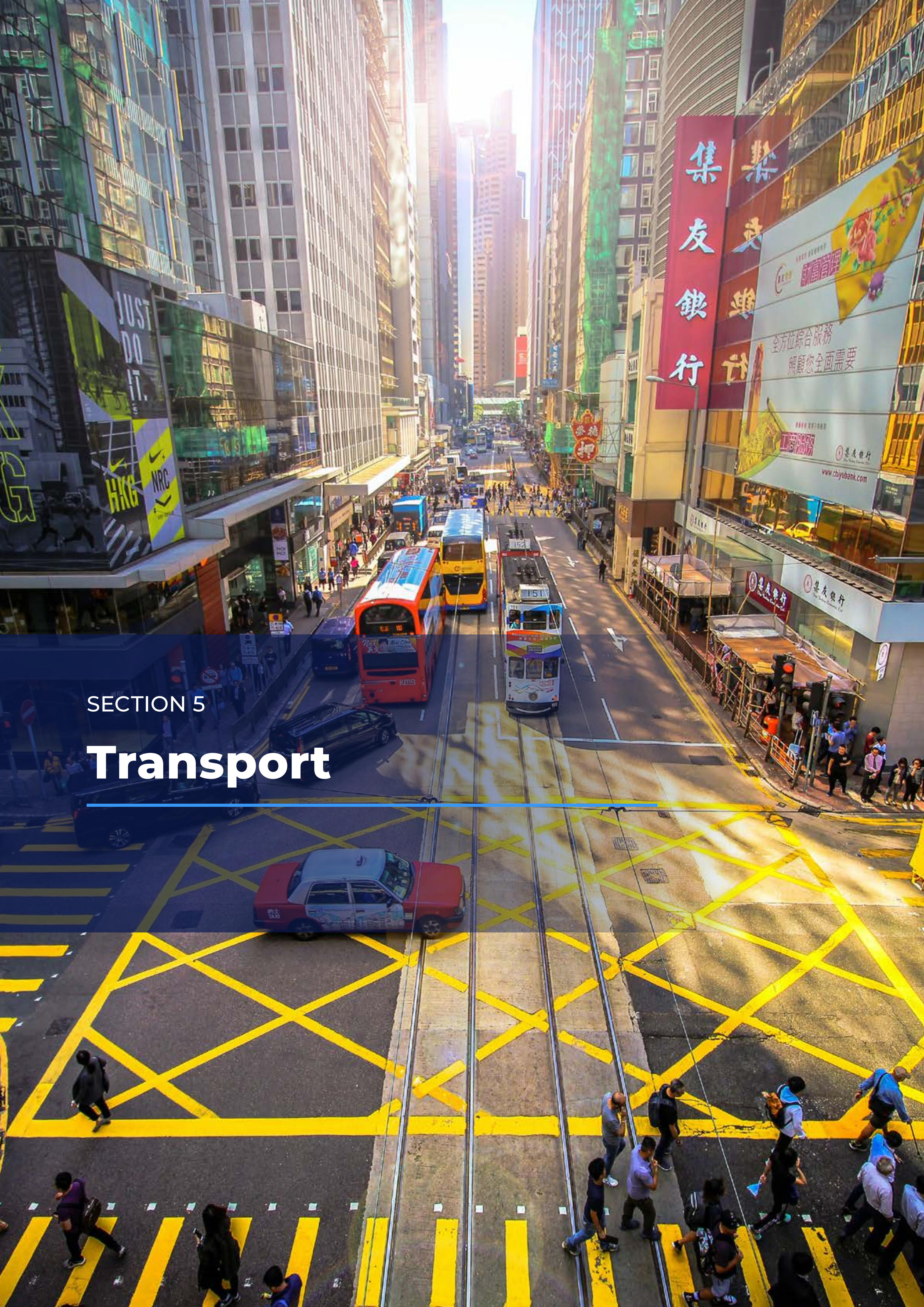
Defining what qualifies as green hydrogen is an important aspect of hydrogen strategy development, target setting, trade, and policy development. In early 2023, the European Parliament adopted a definition for renewable hydrogen that could serve as a starting point for developing consistent national or international standards (Day 2023). It includes a wide range of rules linked to different low-carbon hydrogen technologies, such as natural gas with CCS, nuclear-based electricity and electrolysis, and renewable-based electrolysis. It also has renewable energy additionality rules to ensure that existing capacities are not used to produce green hydrogen instead of decarbonizing the grid (European Parliament 2023b).

Demand for green hydrogen can incentivize new investments in expanded production capacity. In addition to increasing demand from the steel sector (see "Recent developments in lowering the carbon intensity of steel" above), green ammonia production—a derivative of green hydrogen that can be used as a zero-carbon feedstock in chemicals production—is gaining momentum, with over 60 green ammonia plants, with combined production of 34.1 Mt/year by 2030, announced as of May 2022 (Saygin et al. 2023). Companies in almost all parts of the world are investing in green ammonia plants (*State of Green* 2022; *Hydrogen Central* 2023b; *PR Newswire* 2023; Collins 2022a; *Outlook* 2023; Prisco 2022; *Hydrogen Central* 2023a; Saygin et al. 2023).



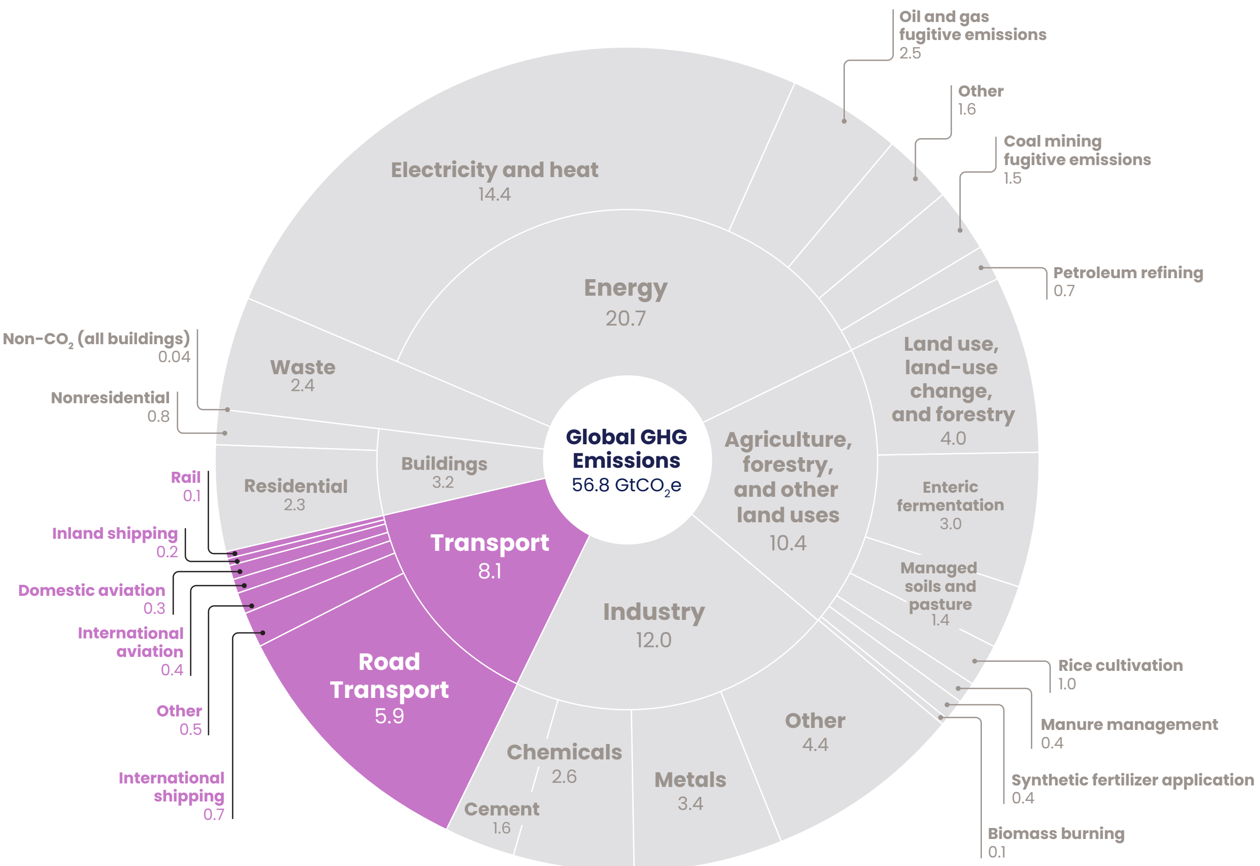
SECTION 5

Transport

Transportation networks connect people to one another, as well as to everything they need to lead fulfilling lives: education, jobs, goods, and services. Yet most current transport paradigms remain inaccessible to many, while also contributing significant carbon pollution to the atmosphere. Since 1990, for example, increased car ownership and travel due to rising incomes has driven steady increases in GHG emissions from transport (IEA 2020b). The global motorization rate grew from 243 vehicles per 1,000 people in 2015 to 277 vehicles per 1,000 people in 2020,[42] although this differs greatly between developed and developing countries. Additionally, vehicles are becoming bigger in places where car dependency is high, such as the United States (Meyer 2023). In fact, emissions are set to at best stagnate through 2050 if further action is not taken, due to increasing transport demand (ITF 2023a). Systemwide, transport emitted approximately 8.1 GtCO$_2$e in 2021, accounting for about 14 percent of direct global GHG emissions (Figure 29) (Minx et al. 2021; European Commission and JRC 2022). Road transport is the largest source of direct emissions in the sector, making up 73 percent of transport emissions in 2021 (Minx et al. 2021; European Commission and JRC 2022). Marine shipping contributed 11 percent of emissions, while aviation followed at 9 percent. Rail only contributed about 1 percent of emissions, and the remaining 6 percent are attributable to miscellaneous transport emissions. Although indirect emissions are not available for 2021, historically they have represented no more than 0.2 GtCO$_2$e each year (IEA 2022i).

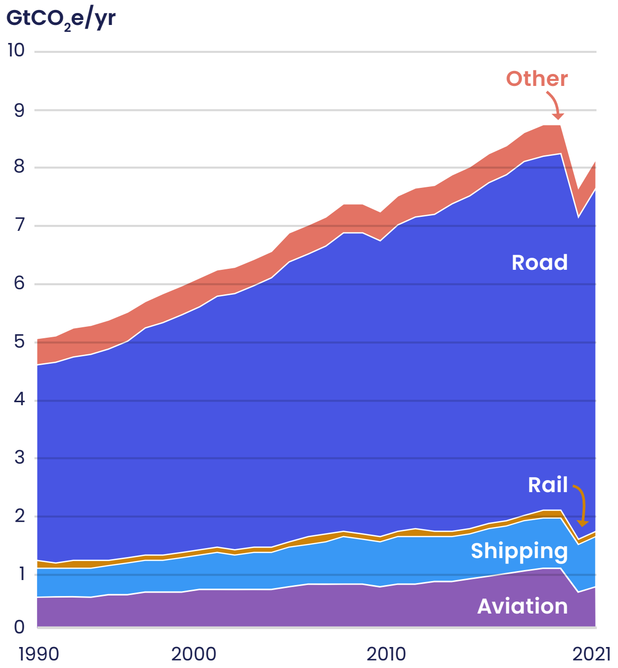
Emissions increased steadily in recent years save for a brief dip in 2020 during early lockdowns caused by the COVID pandemic (Figure 30) (Minx et al. 2021; European Commission and JRC 2022; IEA 2022i). Direct and indirect GHG emissions reached approximately 8.9 GtCO$_2$e in 2019 and temporarily fell to 7.6 GtCO$_2$e in 2020 (Figure 30). Although indirect emissions are not available for 2021, direct emissions exceeded the combined direct and indirect emissions in 2020. Transport experienced the greatest emissions decline from 2019 to 2020 and the strongest rebound of any sector in 2021 (Cardama et al. 2023). And over this same period, the rising ubiquity and dominance of personal cars and their infrastructure have dramatically reduced the ability of people without driver's licenses or high incomes to move safely and affordably.

FIGURE 29 | Transport's contribution to global net anthropogenic GHG emissions in 2021



Notes: CO$_2$ = carbon dioxide; GHG = greenhouse gas; GtCO$_2$e = gigatonnes of carbon dioxide equivalent.
Sources: Minx et al. (2021); European Commission and JRC (2022).

FIGURE 30 | Global direct GHG emissions from transport



Notes: GHG = greenhouse gas; $GtCO_2e/yr$ = gigatonnes of carbon dioxide equivalent per year. Minx et al. (2021) and European Commission and JRC (2022) provide an estimate of direct and indirect GHG emissions from transport through 2020. Data on indirect GHG emissions from transport, specifically, are not yet available for 2021. But because they represent a relatively small share of this sector's total emissions (2.7% in 2020), this figure excludes indirect GHG emissions and includes data from 2021.

Sources: Minx et al. (2021); European Commission and JRC (2022); IEA (2022i).

Global assessment of progress for transport

Transforming the global transportation sector will require fair, equitable, and rapid change on the roads, in the sea, and in the air. On the roads, fossil-fueled vehicles will need to be electrified, and fossil-fueled cars will need be to be replaced, right-sized, and diminished in number. Many more people will need to use active modes (including walking and bicycling) and shared public transport. They will need to reduce both their reliance on cars and their distances traveled, particularly in regions where car dependency is high. Cities will need to build more rapid transit, bike lanes, and facilities for safe, comfortable walking, as well as implement measures to restrict polluting motor vehicles. Beyond road transport, shipping and aviation must decarbonize through a combination of demand-reduction strategies and clean fuels. Regions and countries will need to identify suitable approaches and pathways based on their demographic background, economic dynamics, and financial and institutional capacity. Access to mobility must be increased where it is low, where active modes or public transit are not available due to poor infrastructure or insufficient safety, and where development patterns require car dependency (Table 4).

TABLE 4 | Summary of global progress toward transport targets

INDICATOR	MOST RECENT DATA POINT (YEAR)	2030 TARGET	2035 TARGET	2050 TARGET	LIKELIHOOD OF FOLLOWING AN S-CURVE	ACCELERATION FACTOR	STATUS
Number of kilometers of rapid transit per 1 million inhabitants (km/1M inhabitants)	19 (2020)	38	N/A	N/A	↗	6x[a]	✕
Number of kilometers of high-quality bike lanes per 1,000 inhabitants (km/1,000 inhabitants)	0.0044 (2020)	2	N/A	N/A	↗	>10x[a]	✕
Share of kilometers traveled by passenger cars (% of passenger-km)[b]	45 (2019)	35–43	N/A	N/A	↗	N/A; U-turn needed[a]	↩
Share of electric vehicles in light-duty vehicle sales (%)	10 (2022)[c]	75–95	100	N/A	∫	N/A; author judgment[d]	✓
Share of electric vehicles in the light-duty vehicle fleet (%)	1.5 (2022)[c]	20–40	N/A	85–100	∫	N/A; author judgment[d]	!

TABLE 4 | Summary of global progress toward transport targets (continued)

INDICATOR	MOST RECENT DATA POINT (YEAR)	2030 TARGET	2035 TARGET	2050 TARGET	LIKELIHOOD OF FOLLOWING AN S-CURVE	ACCELERATION FACTOR	STATUS
Share of electric vehicles in two- and three-wheeler sales (%)	49 (2022)[e]	85	N/A	100	∫	N/A; author judgment[d]	!
Share of battery electric vehicles and fuel cell electric vehicles in bus sales (%)	3.8 (2022)[f]	60	N/A	100	∫	N/A; U-turn needed[d]	↩
Share of battery electric vehicles and fuel cell electric vehicles in medium- and heavy-duty commercial vehicle sales (%)	2.7 (2022)[f]	30	N/A	99	∫	N/A; author judgment[d]	✕
Share of sustainable aviation fuels in global aviation fuel supply (%)	0.1 (2022)	13	N/A	100	∫	N/A; author judgment[d]	✕
Share of zero-emissions fuels in maritime shipping fuel supply (%)	0 (2018)	5	N/A	93	∫	N/A; author judgment[d]	✕

Notes: km/1M inhabitants = kilometers per 1 million inhabitants; km/1,000 inhabitants = kilometers per 1,000 inhabitants; passenger-km = passenger-kilometers. See Jaeger et al. (2023) for more information on methods for selecting targets, indicators, and datasets, as well as our approach for assessing progress.

[a] Due to data limitations, an acceleration factor was calculated for this indicator using methods from Boehm et al. (2021).

[b] We calculated this number using the share of passenger-kilometers traveled in light-duty vehicles.

[c] These data differ from those in previous installments of the *State of Climate Action* in that they show only battery electric vehicles and exclude plug-in hybrid vehicles to align historical data with the 2030, 2035, and 2050 targets. We now use data from IEA (2023e).

[d] For indicators categorized as S-curve likely, acceleration factors calculated using a linear trendline are not presented, as they would not accurately reflect an S-curve trajectory. The category of progress was determined based on author judgment, using multiple lines of evidence. See Appendix C and Jaeger et al. (2023) for more information.

[e] Historical data from BloombergNEF (2023), accessed with permission from Bloomberg New Energy Finance.

[f] These data differ from those in previous installments of the *State of Climate Action*. We now use data from IEA (2023e) to align historical data with the 2030 and 2050 targets.

Sources: Historical data from authors' analysis of ITDP (2021); authors' analysis of OpenStreetMap contributors (2021); ITF (2023a); IEA (2023e); BloombergNEF (2023); Air Transport Action Group (2021); Mistry (2022); IATA (2022); and IMO (2020). Targets from Teske et al. (2021); Moran et al. (2018); ITDP (2021); United Nations (2019); Moser and Wagner (2021); Mueller et al. (2018); BloombergNEF (2021b); CAT (2020b); IEA (2021b); MPP (2022d); and UMAS (2021).

The consensus in the literature (e.g., BloombergNEF 2022a; ICCT 2020; and IEA 2021b) points to a mix of supportive policy measures to transform the transport sector. It indicates the need to **avoid** motorized travel by planning cities in such a way that motorized travel is not needed, and **shifting** toward more space- and fuel-efficient, less carbon-intensive modes, such as public transport (Transport Indicator 1) and walking and cycling (Transport Indicator 2). It also stresses the need to **improve** the space-, material-, and fuel-efficiency of vehicles if we are to reduce the carbon intensity of carbon-intensive travel (Transport Indicators 4–10).

Avoid the need for motorized travel

Avoiding motorized travel (including air travel) is one of the most important ways to reduce CO$_2$ emissions. The COVID-19 pandemic offered a glimpse into the types of trips that could be avoided by using technology to work from home. It revealed how many desktop jobs and even services such as doctor's appointments could be held virtually. Better land use planning is another powerful tool for cutting down on transport emissions. Making destinations closer to where people live by, for example, changing planning and zoning regulations to allow for denser, mixed-use areas, can enable people to walk or cycle, rather than drive. Unfortunately, there are no targets that we can refer to for this indicator and we have therefore not included it in this report, but the international community would benefit from indicators and targets for declining household car dependence or, in areas where personal car ownership is high, declining car ownership.

This highlights an influential data-policy feedback loop: The absence of publicly available, standardized, and comparable data impedes the formulation of effective targets, indicators, and policies, which in turn stifles the resources necessary for the generation of further data. This cyclical dynamic underscores the urgent need for comprehensive data collection and transparency, fundamental for effective target setting, policy development, and tracking of the travel avoidance required.

Shift to shared, collective, or active transport[43]

Cars, whether paid-per-use (e.g., taxis or ride hailing) or privately used, emit more CO_2 per passenger-kilometer traveled than all other urban land transport modes (Cazzola and Crist 2020). Therefore, shifting larger motorized travel to other right-sized or shared-passenger modes can help us stay within our CO_2 budget to remain below 1.5°C.

Making this change has proven difficult, partly because governments have prioritized investments in infrastructure and other policy decisions for private automobiles, making driving, which generates multiple externalities, an easy choice (Santos et al. 2010). Multiple supply-and-demand-side measures are needed to reduce dependence on and use of cars. The literature shows that “softer” demand-side measures, such as providing better information about transport externalities and running campaigns to try to change behavior, have yielded modest results (Hrelja and Rye 2022). These therefore need to be complemented by both supply-side measures that improve the safety and quality of nonpersonal-car travel alternatives—improving transit frequency, installing separated cycle infrastructure, improving sidewalks and crosswalks—and “push” measures that make driving private automobiles more expensive or less convenient, and that have proven to be more effective. These measures can include congestion pricing, fuel and vehicle taxation (which can also support “improve” measures), reallocating urban space away from cars toward other modes, and reducing the availability of street parking (Hrelja and Rye 2022; ITF 2023b).

TRANSPORT INDICATOR 1:

Number of kilometers of rapid transit per 1 million inhabitants (km/1M inhabitants)

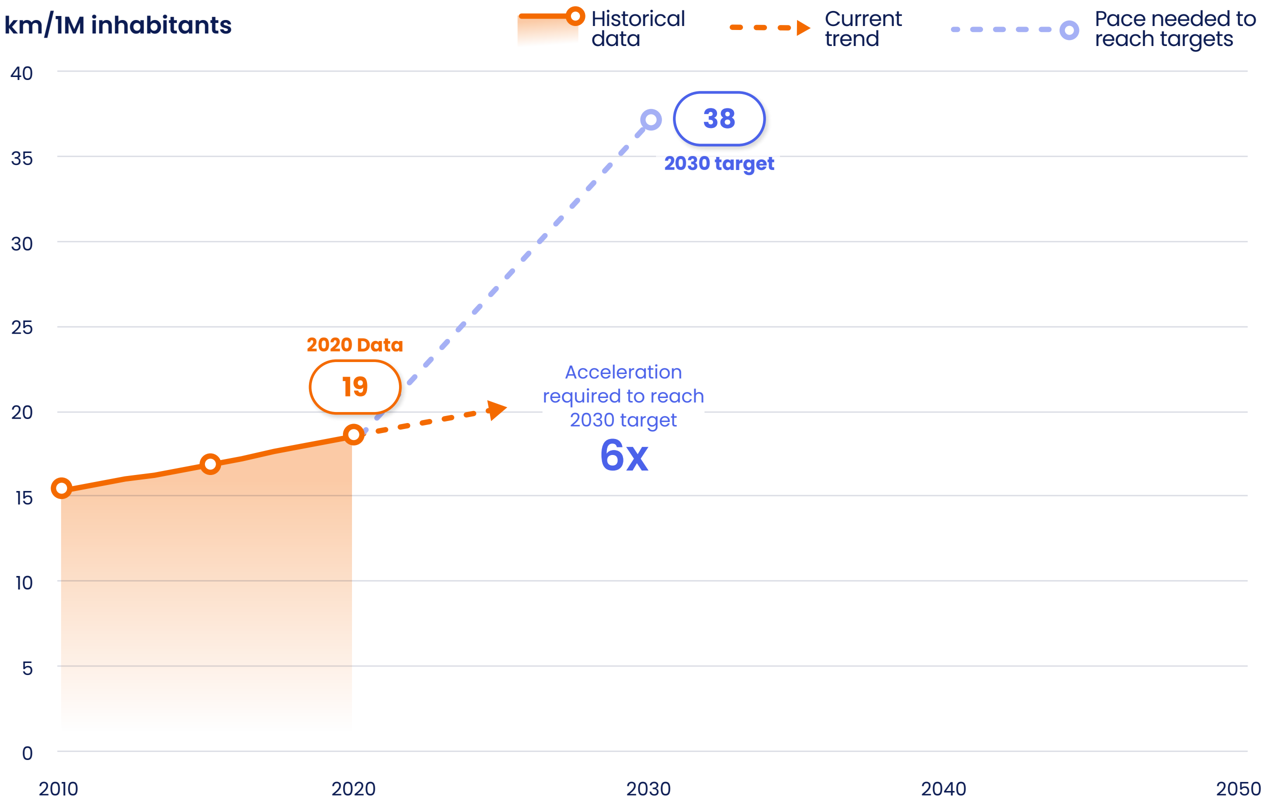
- **Target:** Across the world's 50 highest-emitting cities, rapid transit infrastructure, specifically metro, light-rail, and bus rapid transit as measured in kilometers per 1 million inhabitants, doubles by 2030, relative to 2020.

Making high-quality transit available in urban areas is an effective tool to propel modal-shift, and a good complement to other policy and taxation measures such as reducing free parking availability, reducing car lanes, removing fuel subsidies, or levying taxes to raise fuel prices (Batty et al. 2015). Buses and trains (including metro systems) are particularly crucial for decarbonizing the transport sector. They release as little as a fifth of the emissions of ride-hailing, and about a third of the emissions of private vehicles per passenger-kilometer traveled (ITF 2020). The number of kilometers of rapid transit infrastructure per 1 million inhabitants in the top 50 emitting cities has increased over time, from 16 in 2010 to 19 in 2020 (Figure 31). Europe outpaces the rest of the world in terms of its rapid-transit-to-resident ratio, with Chile, Ecuador, South Korea, and Tunisia following (ITDP 2021).[44] Due to the slow growth, the indicator is heading in the right direction but well off track. An acceleration of six times the rate of recent change is needed.

FIGURE 31 | Historical progress toward 2030 target for number of kilometers of rapid transit per 1 million inhabitants (top 50 emitting cities)

☒ **Right Direction, Well Off Track**

S-Curve Unlikely



Notes: km/1M inhabitants = kilometers per 1 million inhabitants. Due to data limitations, an acceleration factor was calculated for this indicator using methods from Boehm et al. (2021). See Jaeger et al. (2023) for more information on methods for selecting targets, indicators, and datasets, as well as our approach for assessing progress.

Sources: Historical data from authors' analysis of ITDP (2021). Target derived from Teske et al. (2021); Moran et al. (2018); ITDP (2021); and United Nations (2019).

TRANSPORT INDICATOR 2:

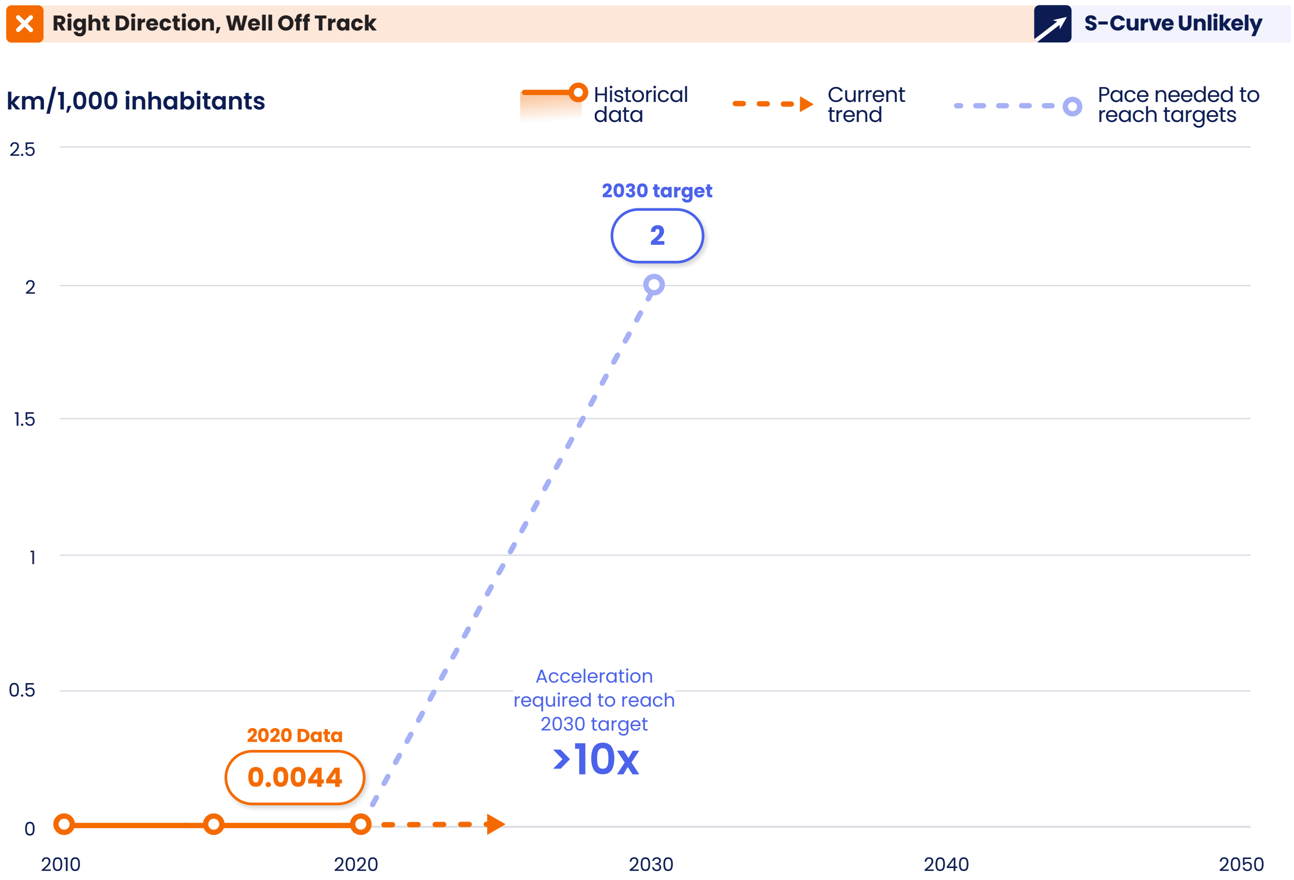
Number of kilometers of high-quality bike lanes per 1,000 inhabitants (km/1,000 inhabitants)

- **Target:** Across the world's 50 highest-emitting cities, urban areas contain two kilometers of high-quality, safe bike lanes per 1,000 inhabitants by 2030.

Creating high-quality bike networks helps reduce CO_2 emissions by making it possible to avoid car trips (Prasara and Bridhikitti 2022). Cycling infrastructure has been shown to significantly increase uptake of cycling, because it promotes actual and perceived safety (Reynolds et al. 2009). Cycling infrastructure has also been shown to improve health outcomes through lower rates of disease and fewer injuries (Maizlish et al. 2017). Furthermore, biking infrastructure costs much less than other transport infrastructure such as mass transit, making bike networks a highly cost-effective policy to mitigate CO_2 emissions (Reich et al. 2022).

In 2020, there were approximately 0.0044 kilometers of high-quality bike lanes per 1,000 inhabitants in the top 50 emitting cities.[45] Bike use surged during the COVID-19 pandemic. For example, Bogotá (although not one of the top-50 emitting cities) expanded its network of bike lanes during the pandemic to encourage social distancing while traveling (Box 11). European countries like Denmark, the Netherlands, and Germany are leading in creating safe, convenient, and accessible cycling conditions with bike networks that extend throughout cities and across their entire countries. Cities like Paris (a top-50 emitting city) have set bold aspirations to construct safe biking infrastructure that provides access by bicycle to all areas of the city and have also reduced the number of on-street parking spaces and lanes available to car travel, as well as the posted speed limit (City of Paris 2021; Pucher and Buehler 2008), Paris now has more than

FIGURE 32 | Historical progress toward 2030 target for number of kilometers of high-quality bike lanes per 1,000 inhabitants (top 50 emitting cities)



Notes: km/1,000 inhabitants = kilometers per 1,000 inhabitants. Due to data limitations, an acceleration factor was calculated for this indicator using methods from Boehm et al. (2021). See Jaeger et al. (2023) for more information on methods for selecting targets, indicators, and datasets, as well as our approach for assessing progress.

Sources: Historical data from authors' analysis of OpenStreetMap contributors (2021). Target derived from Moser and Wagner (2021); Mueller et al. (2018); and Moran et al. (2018).

150 kilometers of bike lanes, with 52 of these added since the pandemic; among other measures, this has helped lead to a 60 percent reduction in car trips within the city between 2011 and 2018 (Atelier Parisien d'Urbanisme 2021). Another important development making cycling more accessible to many is the growing availability of affordable electric bikes (see Indicator 6).

The recent rate of change remains well off track and will need to increase more than 10-fold by 2030 to be aligned with a 1.5°C pathway (Figure 32). Walking and bicycling are significantly less expensive than buying a new or used motorized passenger vehicle (ITDP 2022). Arguably, investing in active transportation modes and making it easier to get around without a car would be more equitable than microtargeting subsidies for electric cars since, in the United States, these incentives have been shown to be regressive, disproportionately benefiting higher-income households (Congressional Research Service 2019). In existing urban developments, the addition of bike lanes can replace on-street parking or car lanes, making car use less convenient. Bike lanes can also avoid conflicts between cyclists and both motorized vehicles and pedestrians (and, in particular, people with disabilities who need unencumbered sidewalks) (Shoman and Imine 2023).

BOX 11 | Lessons learned from bike lanes in Bogotá

The Colombian capital, Bogotá, represents an impressive story in popularizing cycling. Starting in the 1970s, pushed by cycling advocates, the city established its open streets event (Ciclovía), currently the largest and most frequent event of this type in the world. Every Sunday, the city opens 128 kilometers (80 miles) of streets for the enjoyment of 1.5 million pedestrians and cyclists, with multiple events along the route such as Zumba classes, food vendors, and entertainment.

In addition to this event, starting in the 1990s, the city has been building bike lanes and making it easier to get around by bicycle, constructing 550 kilometers (342 miles) of dedicated bike lanes by 2019. In 2020,

FIGURE B11.1 | Map of the original and new temporary bike lanes

Source: Ramírez (2021).

BOX 11 | Lessons learned from bike lanes in Bogotá (continued)

following travel pattern changes due to the COVID-19 pandemic, and to give people alternatives to the crowded public transport system, the mayor started adding another 49 kilometers (30 miles) of temporary (or "pop-up") bike lanes, later expanded to 84 kilometers (52 miles). Initially, these temporary bike lanes consisted of nothing more than traffic cones or plastic bollards along major traffic corridors that gave people a safe way to travel between destinations (Figure B11.1). After the health emergency had ended, the city kept some of the temporary bike lanes and made them permanent, bringing its total network to 593 kilometers (368 miles)—or approximately 0.08 km/1,000 inhabitants.

The systematic construction of bike lanes that started in the 1990s has paid off. In 1996, only 0.68 percent of daily trips in the city were done by bicycle (Cervero et al. 2009). Just before the pandemic, bicycle trips in the city totaled over 800,000 trips (or 6.6 percent of all trips done in the city). While the COVID-19 pandemic lockdown made a dent in the growth, as trips in April 2020 more than halved to 360,000 daily bike trips, the city's quick thinking with the temporary bike lanes helped grow the daily trips to 650,000 by December 2020 (Ramírez 2021). This shows that the constant investment in creating and expanding the bike network has had its intended effect, giving Bogotanos more choices to access their daily needs in a sustainable and healthy manner.

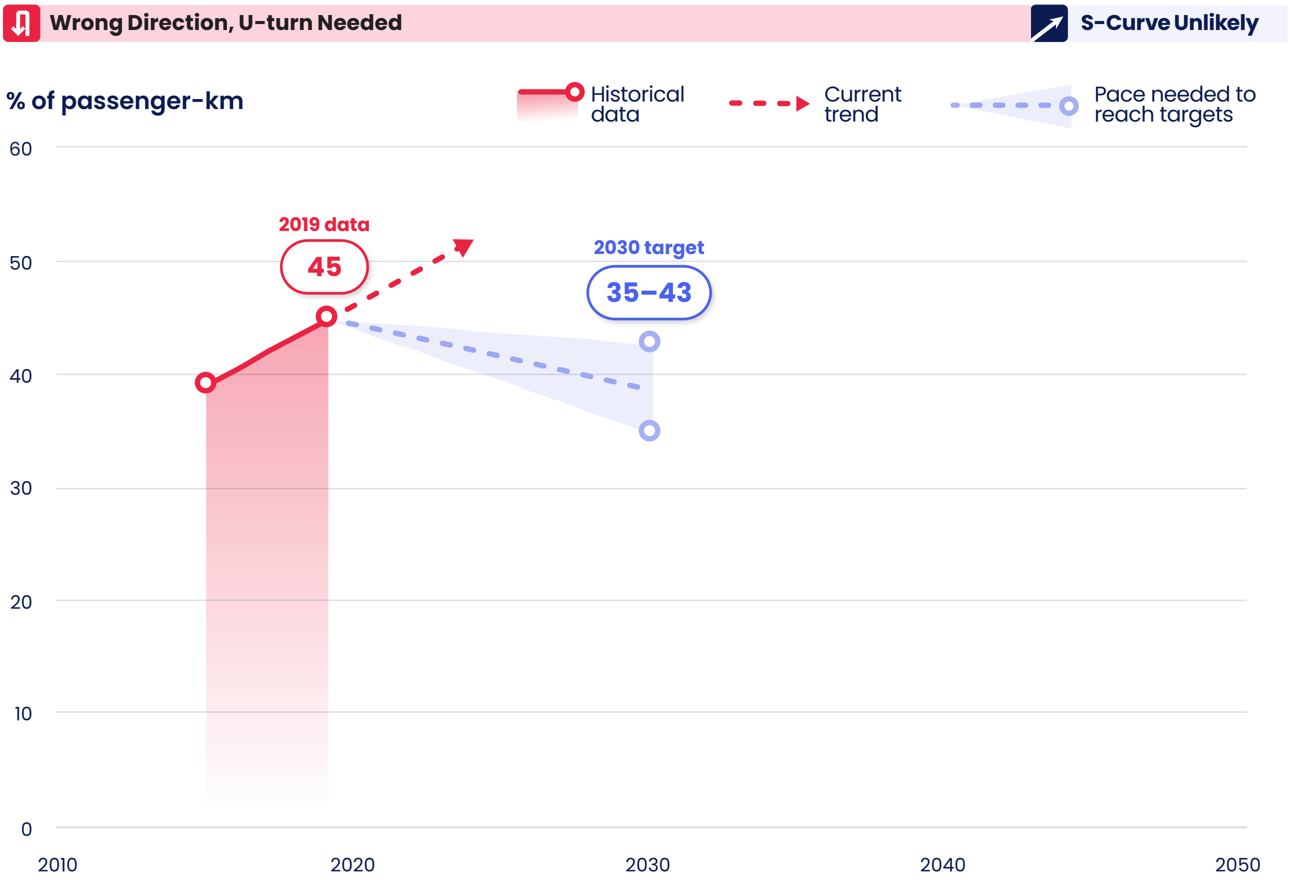
This transformation has been made possible by a mix of factors. The city has active advocacy groups that have pushed for pro-bike transformations at least since the 1970s. This was the likely result of an already established bike culture in the country since the 1950s (Welch 2021). These empowered activist circles, supported by Bogotá's mayors in the 1990s, pushed for the creation of over 70 percent of the network we see today. Other contributing factors include policies such as the annual "car-free" day, which demonstrate that the city can function without cars, the city's extensive bus network, its license plate-based decongestion pricing, and restrictions on what days and hours cars can circulate. These policies are now being complemented by the recently inaugurated public bike share network.

TRANSPORT INDICATOR 3:
Share of kilometers traveled by passenger cars (% of passenger-kilometers)

- **Target:** People around the world reduce the percentage of trips made in passenger cars to 35–43 percent by 2030.

While extensive historical data are not available on the share of passenger-kilometers traveled in passenger cars, the data that do exist show a worrying trend. The share of passenger-kilometers traveled in passenger cars increased from 39 percent in 2015 to 45 percent in 2019 (the most recent data point), indicating that change is heading in the wrong direction entirely (Figure 33) (ITF 2023a). The cause of this increase is understandable: as population and gross domestic product (GDP) have grown, so has the number of people who own cars, and therefore the share of trips made by privately owned cars (World Bank 2014). Furthermore, the COVID-19 pandemic led to a drop in demand for public transport and the rate of recovery of the demand for these systems post-COVID has varied widely, with some systems seeing patronage return to prepandemic levels or above, while others have not. The trend in car ownership is expected

FIGURE 33 | Historical progress toward 2030 target for share of kilometers traveled by passenger cars



Notes: passenger-km = passenger-kilometers. We calculated this number using the share of passenger-kilometers traveled in light-duty vehicles. Due to data limitations, an acceleration factor was calculated for this indicator using methods from Boehm et al. (2021). See Jaeger et al. (2023) for more information on methods for selecting targets, indicators, and datasets, as well as our approach for assessing progress.

Sources: Historical data from ITF (2023a); 2030 target derived from authors' analysis of BloombergNEF (2021b), accessed with permission from Bloomberg New Energy Finance.

to be exacerbated mostly by increases in developing countries as GDP continues to grow. In wealthy countries with significant personal car use, the goal should be to reduce car dependency. In countries with low personal-car ownership, the goal should be to slow down the embrace of car ownership. In Asia, for example, private automobiles make up 33 percent of passenger-kilometers traveled, whereas in the United States and Canada their share is 77 percent (ITF 2021).

Improve carbon-intensive modes of transport

Road transport, aviation, and maritime shipping have long been powered by cars, trucks, planes, and ships that run on fossil fuels. Regulations to increase the fuel efficiency of these vehicles have been effective at reducing their GHG emissions—in the United States, they have prevented 14 gigatonnes of CO_2 from being emitted since 1975 (Greene et al. 2020). But simply increasing efficiency is not enough to truly transform the sector, and alternatives are emerging that make it possible to provide a similar experience without contributing planet-warming gases to the atmosphere. Electric versions of road vehicles have proliferated as battery prices have fallen and electric vehicles have become cheaper to own and operate.[46] Light-duty vehicles and two- and three-wheelers have been electrifying the fastest, but medium- and heavy-duty vehicles and buses are beginning to emerge in major markets. Across all vehicle segments, charging infrastructure—both private and public—will be key to increasing uptake of electric vehicles. Solutions for aviation and marine shipping, including those powered by zero-emissions liquid fuels or even electricity, are in development but are only recently beginning to be deployed. As these solutions begin to come to market, it will become clearer what mix of technologies will ultimately win out and succeed at decarbonizing the sector.

TRANSPORT INDICATOR 4:
Share of electric vehicles in light-duty vehicle sales (%)

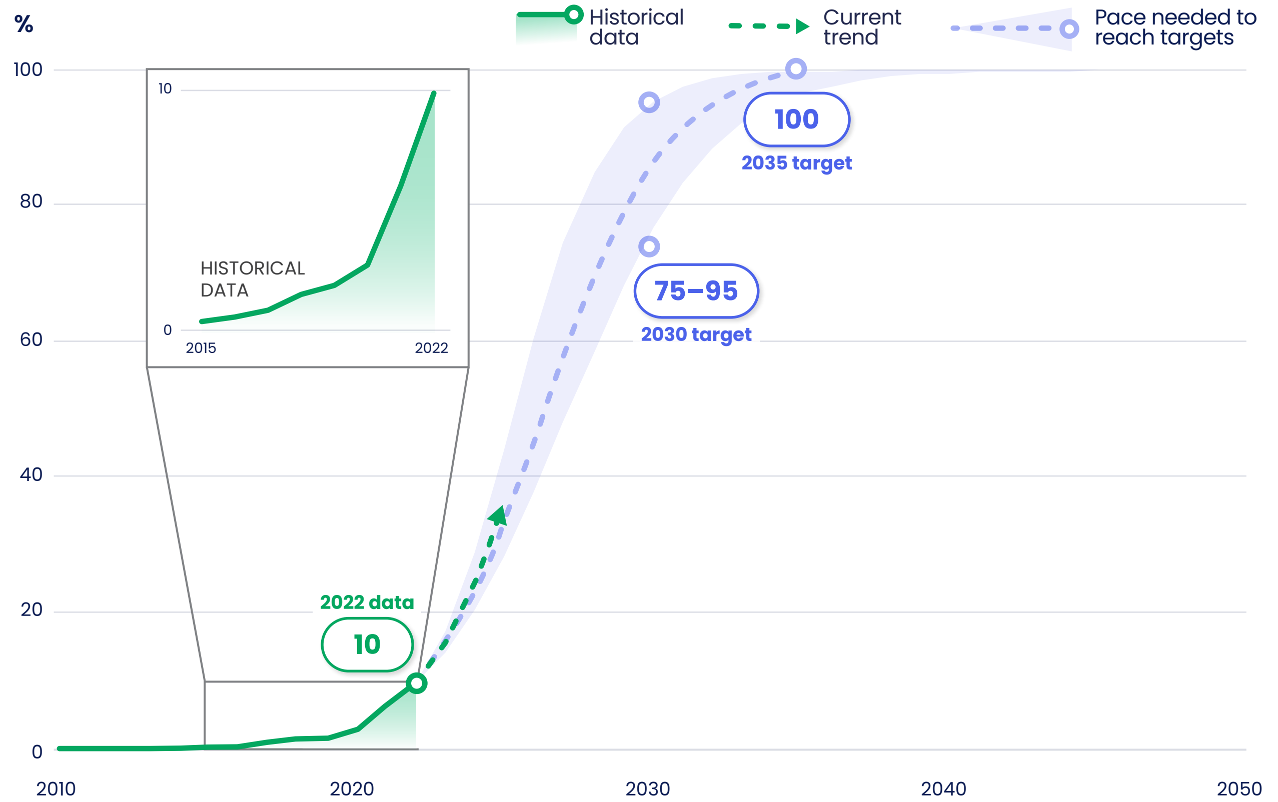
- **Targets:** Electric vehicles (EVs) account for 75–95 percent of the total annual light-duty vehicle (LDV) sales by 2030 and 100 percent by 2035.[47]

The share of battery EVs in global LDV sales has begun to take off recently, reaching 10 percent in 2022 (Figure 34) (IEA 2023e). This represents over 7 million electric cars sold. Over the past five years, light-duty EV sales have grown at an average of 65 percent per year. In 2022, the share of electric vehicles in light-duty vehicle sales increased 63 percent—a meaningful improvement relative to recent trends. Much more progress will be needed to reach 75–95 percent of light-duty vehicle sales by 2030, especially in developing economies, where sales are significantly lower than in developed countries, but EV sales are in the breakthrough stage of an S-curve and will likely continue to accelerate in the coming years. Given the high likelihood for continued rapid exponential change due to favorable long-term cost trends and improvements in range and the availability of charging infrastructure, progress made toward reaching this near-term target is categorized as on track (BloombergNEF

FIGURE 34 | Historical progress toward 2030 and 2035 targets for share of electric vehicles in light-duty vehicle sales

✓ **Right Direction, On Track**

S-Curve Likely



Note: These data differ from those included in previous installments of the *State of Climate Action* in that they show only battery electric vehicles and exclude plug-in hybrid vehicles to align historical data with the 2030 and 2035 targets. We now use data from IEA (2023e). For indicators categorized as S-curve likely, acceleration factors calculated using a linear trendline are not presented, as they would not accurately reflect an S-curve trajectory. The category of progress was determined based on author judgment, using multiple lines of evidence. More specifically, given that this indicator is in the breakthrough stage of an S-curve, our current trend arrow is an S-curve fit to the historical data. Our assessment of progress was made based on this extrapolation, as well as a review of the literature and consultations with experts. See Appendix C and Jaeger et al. (2023) for more information on methods for selecting targets, indicators, and datasets, as well as our approach for assessing progress.

Sources: Historical data from IEA (2023e); targets from CAT (2020b).

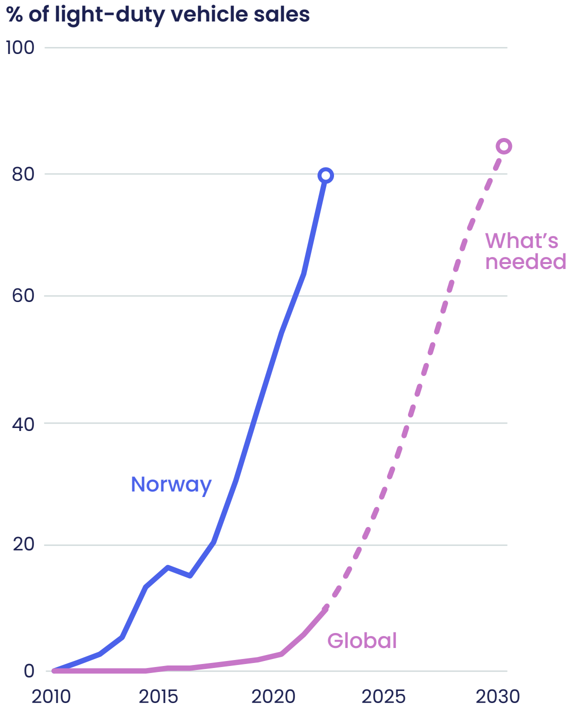
2022a; Grubb et al. 2021; IEA 2023e). Battery manufacturing throughput (the amount that gets produced by manufacturing plants) almost doubled from 340 GWh in 2021 to 660 GWh in 2022, with 90 percent of new manufacturing capacity dedicated to EV batteries (IEA 2023i). When it comes to delivering completed vehicles, however, it will be important to watch whether automakers increase their pledges to produce enough EVs to keep up with sales. As of early 2023, automakers' pledges for future manufacturing were not enough to meet EV sales targets (Punte 2023).

Sales are not even across all geographies. EV sales in China reached 22 percent of total new car sales in 2022, while the European Union saw a 12 percent share and the United States saw an 6 percent share (IEA 2023f). In other countries, sales remain low. To avoid a two-tiered global market, it is important that developed markets and development banks provide assistance to developing countries to grow their EV markets and charging infrastructure. Historically, China has driven much of the growth of EVs, due in part to its generous subsidy provided by both national and local governments for the purchase of electric cars. At its peak, the subsidy could be as high as 10,000 yuan (the equivalent of about $11,000 in 2023 U.S. dollars) (GIZ 2014), depending on range and drivetrain. Buses could receive as much as 500,000 yuan (the equivalent of about $90,000 in 2023 U.S. dollars). The subsidy has expired as of 2023 (although there is still a purchase tax exemption for EVs), and it appears that EVs are continuing to sell well without the subsidy (Li and Kim 2023). Other countries have seen significant growth as well. Norway has been at the forefront of promoting EVs. In 2009, EVs made up 0.3 percent of its new car registrations (European Commission 2023c). Then Norway implemented a raft of incentives, including exemptions from purchase and value-added taxes and access to bus lanes (Richardson 2020). EVs' share of new car registrations in Norway soared to 80 percent in 2022 (IEA 2023f). Norway began scaling back its EV incentives somewhat in 2022 and has been encouraging a shift away from driving toward other modes of transportation (Mossalgue 2022). While differences in per capita income and other factors may make it harder to replicate Norway's strategy everywhere, its success shows that rapid change is possible and that these policies can help drive rapid transformation. From now to 2030, the world needs to scale up electric vehicles at the same pace as Norway did (Figure 35).

The relatively higher purchase price of EVs raises concerns over how accessible EVs are to lower-income consumers (Caulfield et al. 2022). In the United States, 56 percent of EVs bought between 2011 and 2015 went to purchasers making over $100,000 per year, and the top 10 percent of households filing taxes claimed 60 percent of plug-in EV tax credits (Borenstein and Davis 2016; Muehlegger and Rapson 2019). It is fair to assume that as these vehicles age and are sold on the second-hand market, the profile of the purchasers will change. Additionally, more recent analysis in the United States has found that because low-income households spend a larger share of their income on driving costs, EVs will provide greater cost savings as a share of income to low-income households by 2030 (Bauer et al. 2021).

Additionally, it is important to note that increasing lithium mining for EV batteries could further harm the environments where it is mined, with the potential to contaminate groundwater and worsen local air pollution if mining processes are not improved (Penn and Lipton 2021). Efforts such as the Initiative for Responsible Mining Assurance—which brings together mining companies, mineral purchasers, human rights groups, labor groups, and other civil society organizations—are attempting to find consensus on improving these processes (IRMA n.d.). Improvements in alternative battery chemistries that use different combinations of minerals could also help alleviate some of these supply chain constraints.

FIGURE 35 | Share of electric vehicles in light-duty vehicle sales in Norway and the world



Note: These data only include battery electric vehicles.

Sources: Historical global data from IEA (2023e); targets from CAT (2020b).

TRANSPORT INDICATOR 5:

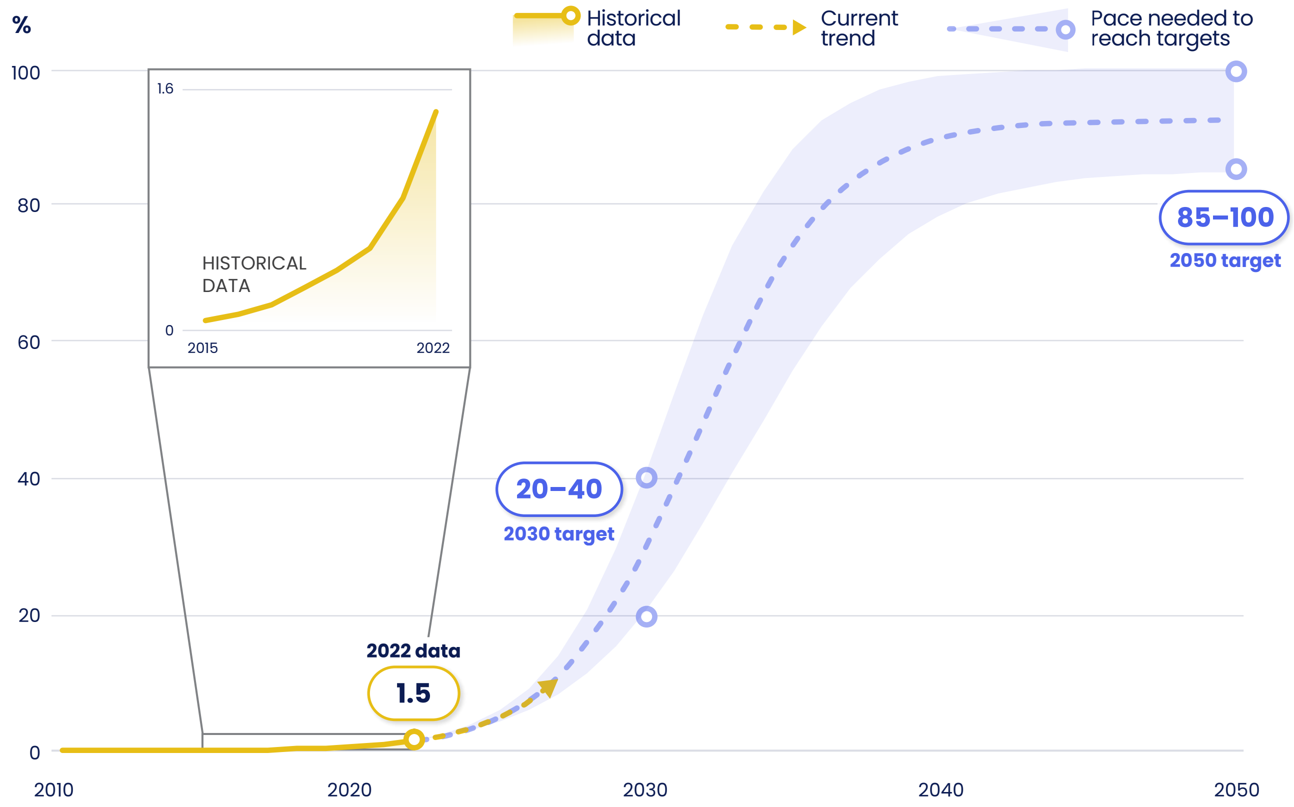
Share of electric vehicles in the light-duty vehicle fleet (%)

- **Targets:** Electric vehicles (EVs) account for 20–40 percent of the total light-duty vehicle (LDV) fleet by 2030 and 85–100 percent by 2050.

Exponential change is occurring in the deployment of battery electric light-duty vehicles on the road.[48] Over the last five years the share of EVs in the global LDV fleet rose by an average of 54 percent per year. Between 2021 and 2022 it almost doubled—a meaningful improvement relative to recent trends. Rapidly growing sales volumes in the key markets of China, the European Union, and now the United States, have led to greater overall EV numbers, with combined total EV numbers in these three major markets rising from a little under 1 million on the road in 2016, to 16 million on the road by 2022 (IEA 2023e). Still, the actual share of EVs is quite low: 1.5 percent in 2022 (Figure 36), which adds up to 18 million electric cars on roads around the world (IEA 2023e). Continued exponential change will be needed to reach 20–40 percent by 2030. As with light-duty EV sales, the share of EVs in the light-duty fleet will likely follow an S-curve, especially as the economics and range of EVs improve and as charging becomes more available. But because new car sales do not necessarily correspond with equal removal of old cars from the market, the share of EVs on the road may lag well behind increases in sales (Keith et al. 2019). As of now the indicator remains in the emergence phase of an S-curve, and it is difficult to determine the trajectory of change at such an early point. Global progress made toward this near-term target is off track based on our assessment of the literature and consultations with experts (see Methods section and Appendix C).

FIGURE 36 | Historical progress toward 2030 and 2050 targets for share of electric vehicles in the light-duty vehicle fleet

! Right Direction, Off Track | **S-Curve Likely**



Notes: These data differ from those included in previous installments of the *State of Climate Action* in that they show only battery electric vehicles and exclude plug-in hybrid vehicles to align historical data with the 2030 and 2050 targets. We now use data from IEA (2023e). For indicators categorized as S-curve likely, acceleration factors calculated using a linear trendline are not presented, as they would not accurately reflect an S-curve trajectory. The category of progress was determined based on author judgment, using multiple lines of evidence. More specifically, our current trend arrow is based on an S-curve fit to the historical data, but such an extrapolation is highly uncertain when an indicator is in the emergence stage of an S-curve and is included for illustrative purposes only. Our categorization of progress for this indicator is based on a review of the literature and consultations with experts. See Appendix C and Jaeger et al. (2023) for more information on methods for selecting targets, indicators, and datasets, as well as our approach for assessing progress.

Sources: Historical data from IEA (2023e); targets from CAT (2020b).

An equity concern emerging as EV fleets grow is the contrast between developed countries, where new car sales are common, and developing countries, where used cars are frequently imported from developed countries. From 2015 to 2020, the European Union, Japan, South Korea, and the United States exported 23 million used light-duty vehicles (LDVs) (UNEP 2021g). Of exported LDVs, 70 percent went to developing countries, most of which do not have strong emissions standards. As a result, developed economies are exporting high-emitting and unsafe secondhand vehicles to developing countries, shifting the transition burden to them. Strong export standards in exporting countries can help reduce the burden on importing countries, but import standards can also help prevent major emitters from exporting dirty cars to low-income countries that need greater access to mobility. The implication of these standards without other domestic market changes, however, would be a slower rate of motorization, which is not necessarily positive for social welfare, so care must be taken to balance these concerns.

In addition to shifting some of the transition burden to low-income countries, the growth of the EV market could change the labor landscape in the automotive industry. There is evidence that electrification will drive changes in manufacturing—especially of components, since electric drivetrains require fewer of these (Fraunhofer IAO 2020). However, looking at the entire manufacturing and deployment process provides a more complicated picture. Although jobs may decrease in manufacturing cars, many new opportunities may arise in providing electricity and/or hydrogen for zero-emissions vehicles as well as EV charging and battery manufacturing. For example, in Europe, which manufactured about 22 percent of the world's passenger cars in 2022 (OICA 2023), one recent study estimates that tightening fuel economy standards would drive a net increase of 43,000 auto sector jobs by 2030 (Cambridge Econometrics and Element Energy 2018). Those employment gains would subside after 2035 as less complex battery electric vehicles would increasingly take market share. But, at the same time, jobs would soar in electrical equipment and hydrogen for electric and hydrogen vehicles in this scenario. In the United States, which produced 3 percent of the world's passenger cars in 2022, another study estimates that new jobs in the country in electricity infrastructure build-out and steady employment in auto manufacturing employment would offset job losses in vehicle repair due to EVs being cheaper and easier to maintain. Thus, it envisions a transition to EVs leading to a net increase of about 300,000 new jobs in electricity and fuel supply by 2035 (Goldman School of Public Policy 2021). Regardless, transitioning workers from auto manufacturing and component manufacturing jobs to opportunities in growth sectors like electrical equipment and hydrogen would require retraining and economic support for workers.

TRANSPORT INDICATOR 6:

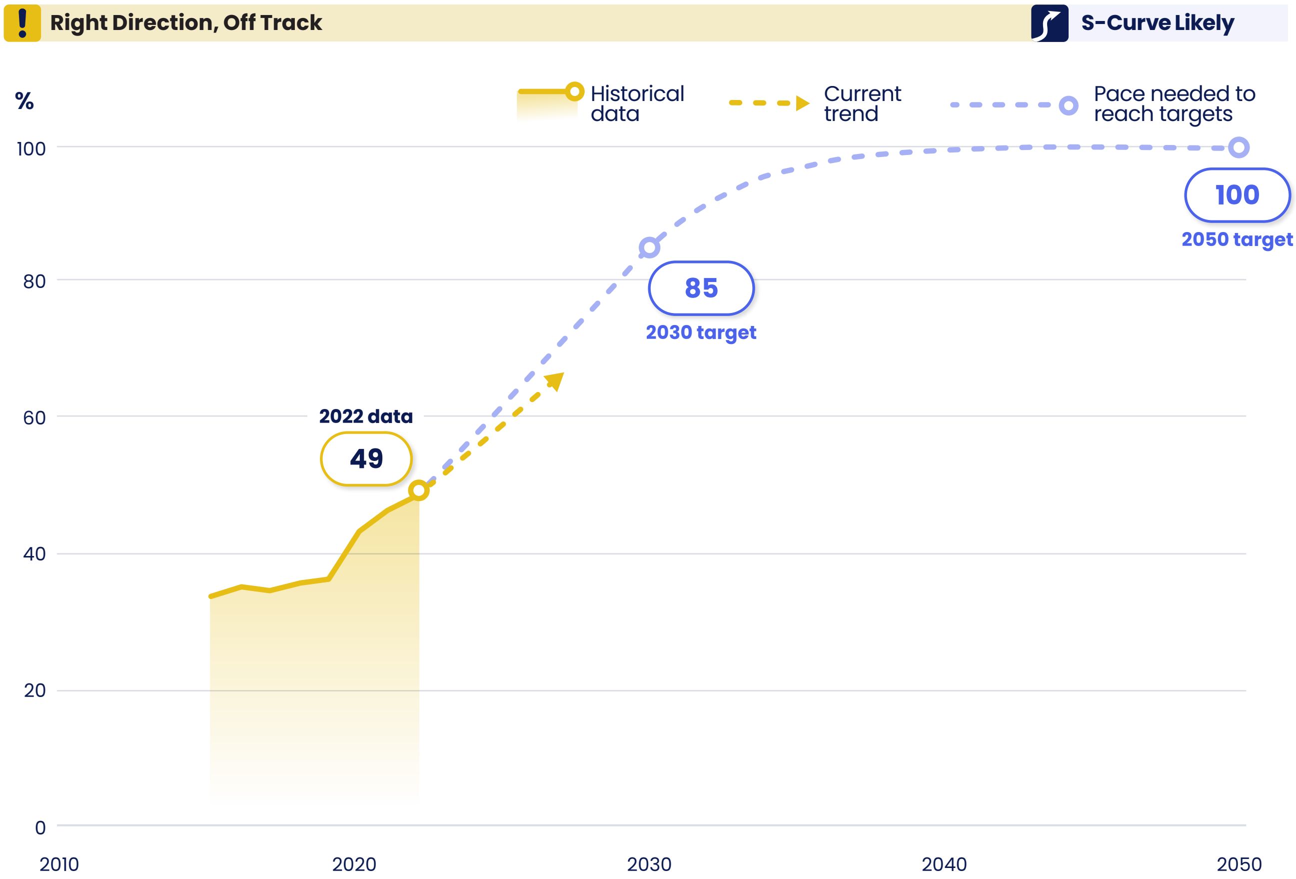
Share of electric vehicles in two- and three-wheeler sales (%)

- **Targets:** Electric vehicles (EVs) account for 85 percent of the total annual two- and three-wheeler sales by 2030 and 100 percent by 2050.

In 2022, a combined 1.2 billion two- and three-wheelers (motorized vehicles with two and three wheels such as motorcycles, rickshaws, tricycles, etc.) were on the road. This rivals the number of passenger cars and trucks (1.26 billion). In certain regions, such as Southeast Asia and India, motorcycles and motorized scooters are the dominant mode of transport, accounting for 83 percent and 80 percent, respectively, of vehicle-kilometers traveled (BloombergNEF 2022a). In absolute numbers, more two- and three-wheelers are sold each year than other passenger and commercial vehicles combined, with markets in China making up more than half of global sales, and substantial shares also coming from India and Southeast Asia, particularly Vietnam (BloombergNEF 2022a).

Although they contributed less than 5 percent of CO_2 emissions from road transport in the last decade (BloombergNEF 2022d), two- and three-wheelers make up 25 percent of the total distance traveled by vehicles on the road (BloombergNEF 2022a). Therefore, to avoid rising emissions, regions dominated by two- and three-wheelers will need to promote zero-carbon versions. This would cut down on pollution and fossil fuel consumption as well. Two- and three-wheelers account for around half of gasoline consumption in India and some Southeast Asian regions (IEA 2022f).

FIGURE 37 | Historical progress toward 2030 and 2050 targets for share of electric vehicles in two- and three-wheeler sales



Note: For indicators categorized as S-curve likely, acceleration factors calculated using a linear trendline are not presented, as they would not accurately reflect an S-curve trajectory. The category of progress was determined based on author judgment, using multiple lines of evidence. More specifically, we do not have sufficient historical data to fit an S-curve to the data, so our current trend is based on the linear trendline from the past five years. This is appropriate because two- and three-wheeler sales are in the diffusion stage of an S-curve, during which growth usually follows an approximately linear path. Our assessment of progress is based on the stage of the S-curve, a review of the literature, and expert judgment. See Appendix C and Jaeger et al. (2023) for more information on methods for selecting targets, indicators, and datasets, as well as our approach for assessing progress.

Sources: Historical data from BloombergNEF (2023), accessed with permission from Bloomberg New Energy Finance; targets from IEA (2021b).

Electrification of these vehicles is already underway, and shares of electric two- and three-wheelers are substantially higher than shares of zero-carbon cars, vans, and trucks. The share of electric vehicles in two- and three-wheeler sales increased from 36 percent in 2019 to 49 percent in 2022 (Figure 37). In China, two-thirds of new two-wheelers and 80 percent of three-wheelers were already electric in 2021 (BloombergNEF 2022a).[49] In many places, electric two- and three-wheelers have already reached cost parity with their fossil-fueled counterparts. They are in fact sometimes cheaper—in India, by as much as 70 percent (IEA 2023e, 2022f), and regions with high shares such as India and Indonesia have purchase incentives in place (IEA 2023e; Rokadiya 2021). One reason for more rapid uptake of EV two- and three-wheelers is the lack of range anxiety—the concern that an electric vehicle will run out of charge during a long journey, which is a smaller problem for two- and three-wheelers, as they are generally used for short, daily commutes. Given regional developments and the advantages that electric two- and three-wheelers have accrued, there is a high likelihood of continued diffusion in countries in addition to India and China (IEA 2023e).

Electric two- and three-wheelers are the types of innovative technologies that generally follow an S-curve. But unlike most of the other indicators in this report that are classified as "S-curve likely," sales of electric two- and three-wheelers are in a later stage of an S-curve, during which further acceleration is less likely. In the diffusion stage of an S-curve, acceleration has already occurred, so the slope of the curve generally proceeds in a linear fashion before eventually slowing down. Indeed, the best fit for the past five years of data for this indicator is a linear trendline. For this reason, we assess progress taking into account the linear trendline, which shows that the indicator is making promising progress but off track. This assessment is corroborated by BNEF's assessment of progress, which finds that electric two- and three-wheelers are almost but not yet on track for a net-zero emissions trajectory (BloombergNEF 2023a).

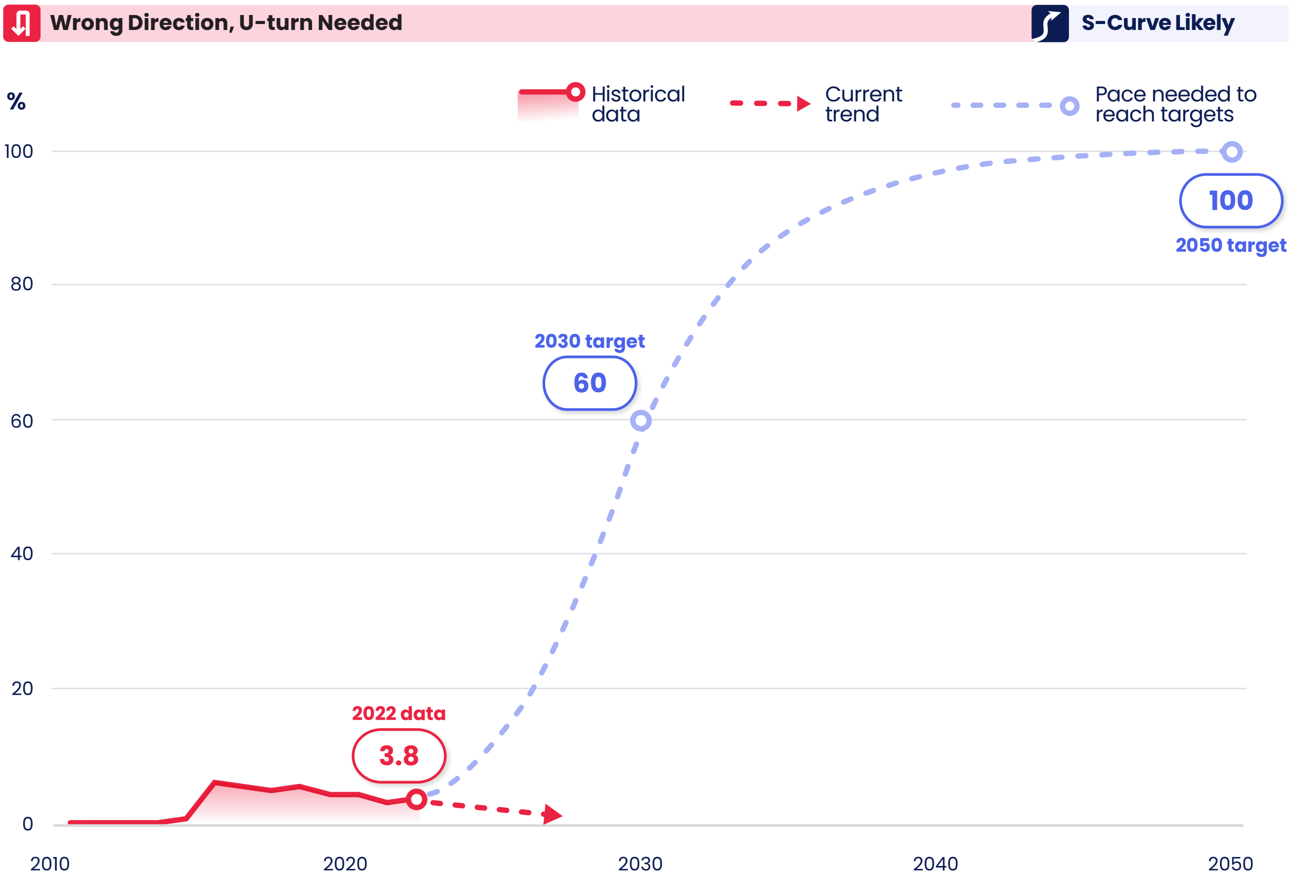
TRANSPORT INDICATOR 7:

Share of battery electric vehicles and fuel cell electric vehicles in bus sales (%)

- **Targets:** Battery electric vehicles (BEVs) and fuel cell electric vehicles (FCEVs) account for 60 percent of the total annual bus sales by 2030 and 100 percent by 2050.

The global share of zero-carbon bus sales has fluctuated, up from just 0.11 percent in 2010 to 3.8 percent in 2022. This was almost entirely due to Chinese demand, which made up 80 percent of zero-carbon bus sales in 2022 (Figure 38) (IEA 2023e). However, this is down from 95 percent in 2010 due to increasing sales in Europe and

FIGURE 38 | Historical progress toward 2030 and 2050 targets for share of battery electric vehicles and fuel cell electric vehicles in bus sales



Note: These data differ from those included in previous installments of the *State of Climate Action*. We now use data from IEA (2023e) to align historical data with the 2030 and 2050 targets. For indicators categorized as S-curve likely, acceleration factors calculated using a linear trendline are not presented, as they would not accurately reflect an S-curve trajectory. The category of progress was determined based on author judgment, using multiple lines of evidence. More specifically, this indicator appeared to approach the breakthrough stage of an S-curve in 2015, but it has since been trending in the wrong direction. So, we reverted to using a linear trendline for the current trend arrow. See Appendix C and Jaeger et al. (2023) for more information on methods for selecting targets, indicators, and datasets, as well as our approach for assessing progress.

Sources: Historical data from IEA (2023e); targets from IEA (2021b).

the United States. Globally, total sales rocketed from 2,000 in 2010 to 63,000 in 2022. There was a dip from 2018 to 2021 due to decreased sales in China before progress picked up again in 2022. Before this dip, the total global fleet increased more than 10-fold between 2014 and 2018 due to strong Chinese demand stimulated by early and continued support, including substantial purchasing and operation subsidies (GIZ 2020). In 2022 sales saw meaningful improvement relative to the recent dip. But considerably more progress will be needed to reach 60 percent of bus sales by 2030 to meet the 1.5°C limit. Past exponential growth in China, alongside increasing sales in Europe and the United States, suggests that rapid progress is possible for zero-carbon buses elsewhere. Additionally, increasing electric bus sales in China in 2022 despite decreasing subsidies over the past few years shows that electric buses are no longer entirely dependent on subsidies (IEA 2023e). Some other countries have seen large electric bus sales shares—including Finland, where 75 percent of bus sales in 2022 were electric (IEA 2023e). Therefore, although the share of bus sales is headed in the wrong direction based on the average rate of change over the last five years,[50] it is possible concerted efforts could turn this trend around and accelerate progress to meet the 2030 goal of 60 percent.

TRANSPORT INDICATOR 8:

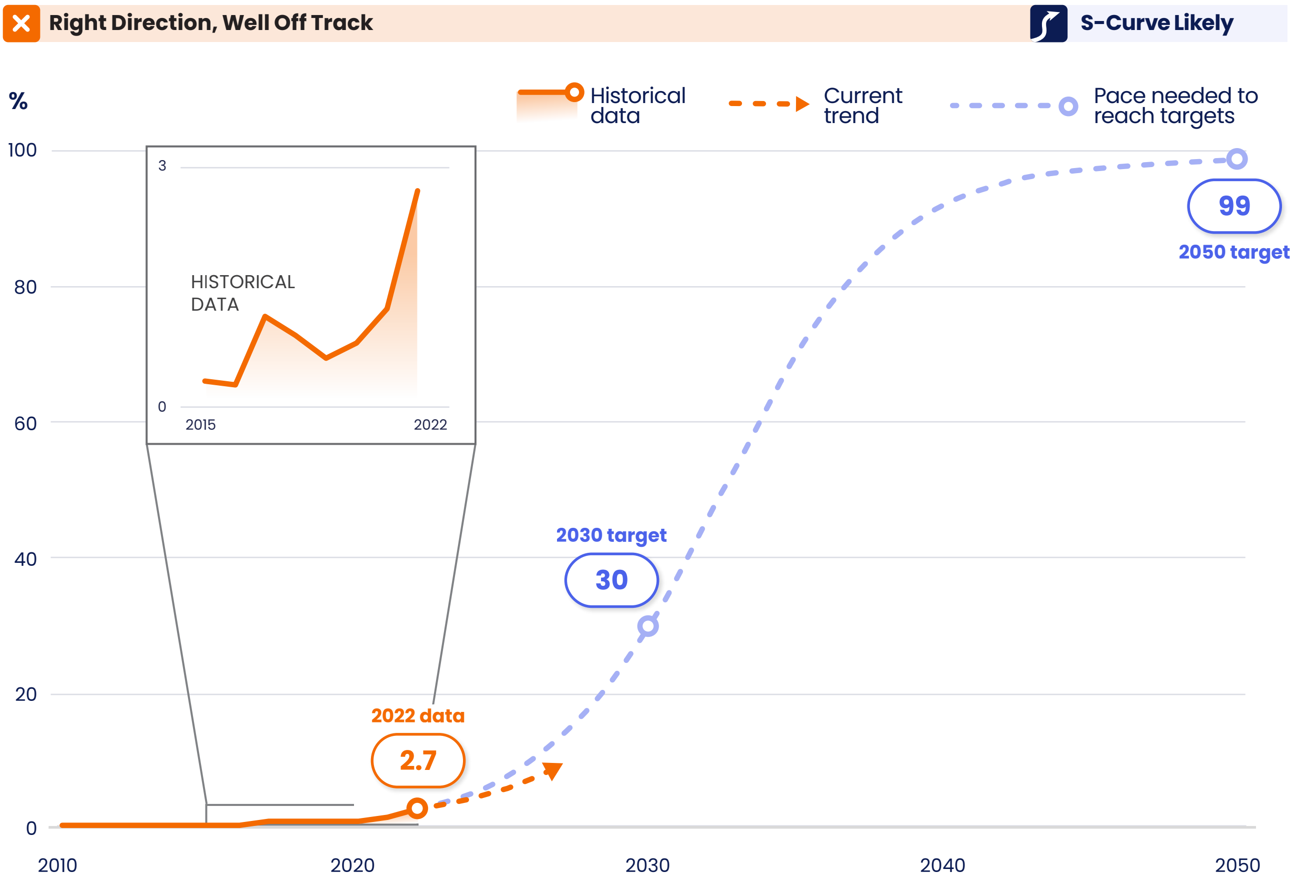
Share of battery electric vehicles and fuel cell electric vehicles in medium- and heavy-duty commercial vehicle sales (%)

- **Targets:** BEVs and FCEVs account for 30 percent of the total annual medium- and heavy-duty commercial vehicle (MHDV) sales by 2030 and 99 percent by 2050.

GHG emissions from heavy-duty vehicles (HDVs) are expected to taper off more slowly than those from light-duty vehicles (LDVs). This is mainly because most big trucks continue to use diesel fuel as electrifying HDVs is more difficult than electrifying LDVs. Moving large vehicles requires much more energy than small vehicles, and batteries must therefore be larger to supply this energy. Larger batteries are heavier, however, and there is a trade-off between the weight of the battery and the weight the truck can haul (Gross 2020). In addition, long-haul trucks have different requirements for range and charging speed than passenger cars. Increasing battery density is expected to alleviate some of these issues (McKerracher 2021), and fuel cells are also considered to electrify heavy-duty transport due to their higher energy densities. However, due to these obstacles to electrification, global GHG emissions from the HDV fleet are projected to be larger than those of the light-duty vehicle fleet by 2025 (Khan and Yang 2022).

Global sales of zero-carbon medium- and heavy-duty vehicles (MHDVs) have risen to 2.7 percent of total sales in 2022—more than double the amount of combined sales in 2021 and a meaningful improvement relative to recent trends (Figure 39). But still, they remain low relative to other categories. Of total electric heavy-duty

FIGURE 39 | Historical progress toward 2030 and 2050 targets for share of battery electric vehicles and fuel cell electric vehicles in medium- and heavy-duty commercial vehicle sales



Note: These data differ from those included in previous installments of the *State of Climate Action*. We now use data from IEA (2023e) to align historical data with the 2030 and 2050 targets. For indicators categorized as S-curve likely, acceleration factors calculated using a linear trendline are not presented, as they would not accurately reflect an S-curve trajectory. The category of progress was determined based on author judgment, using multiple lines of evidence. More specifically, this indicator is categorized as well off track, because it is a new technology that is still in the emergence stage of an S-curve. The current trend arrow is based on an S-curve fit to the historical data, but such an extrapolation is highly uncertain when an indicator is in this early stage and is included for illustrative purposes only. Our categorization of progress for this indicator is based on a review of the literature and consultations with experts. See Appendix C and Jaeger et al. (2023) for more information on methods for selecting targets, indicators, and datasets, as well as our approach for assessing progress.

Sources: Historical data from IEA (2023e); targets from IEA (2021b).

vehicle sales, 85 percent happened in China alone (IEA 2023e). However, European sales increased by a remarkable 80 percent from 2021 to 2022 (EAFO 2023), as automakers began rolling out new models and major logistics companies began purchasing electric heavy-duty trucks. Europe now accounts for 25 percent of global sales (IEA 2023e).

Europe is driving the transition by passing more stringent heavy-duty vehicle standards. Earlier in 2023, for example, the European Commission proposed a revision of its regulation on emissions standards for HDVs. It aims to strengthen the standards for 2030 from a 30 percent reduction of emissions to a 45 percent reduction (from 2019 levels) and would introduce new emissions standards for later years, culminating at a reduction by 2040 of up to 95 percent from 2019 levels (European Commission 2023d). While this is a remarkable step in the right direction, leading to an estimated 550,000 electric truck fleet in Europe by 2030 (Krug 2023), even it falls short of what is needed. Because emissions have surged sharply since 1990, bringing them down 95 percent from 2019 levels implies only a 56 percent reduction from 1990 to 2050, far short of the 100 percent required (Transport and Environment 2023). Efforts in other regions show similar trends in the right direction—California, for example, recently declared it would end all sales of internal combustion engine trucks by 2036 (State of California 2023b).

The share of zero-carbon vehicles in MHDV sales has been growing erratically, including a decrease from 2017 to 2019, but the overall shape of change over the past decade has been roughly exponential. Growth in 2022 was a meaningful acceleration relative to recent trends. Future growth will likely be nonlinear as well. But considerably more progress will be needed to reach 30 percent in 2030. This technology is relatively nascent and remains in the emergence phase of an S-curve. Global progress made toward this near-term target is categorized as well off track. With supportive policies, such as public procurement of municipal MHDVs and sales mandates for manufacturers, the share of zero-carbon MHDVs could reach a breakthrough and increase rapidly and nonlinearly, with adoption rates following an S-curve trajectory of change, especially given increasing model availability and the signs of exponential growth in other EV classes and across various countries and regions (BloombergNEF 2021b).

TRANSPORT INDICATOR 9:

Share of sustainable aviation fuels in global aviation fuel supply (%)

- **Targets:** Sustainable aviation fuels (SAFs) comprise 13 percent of global aviation fuel supply by 2030 and 100 percent by 2050.

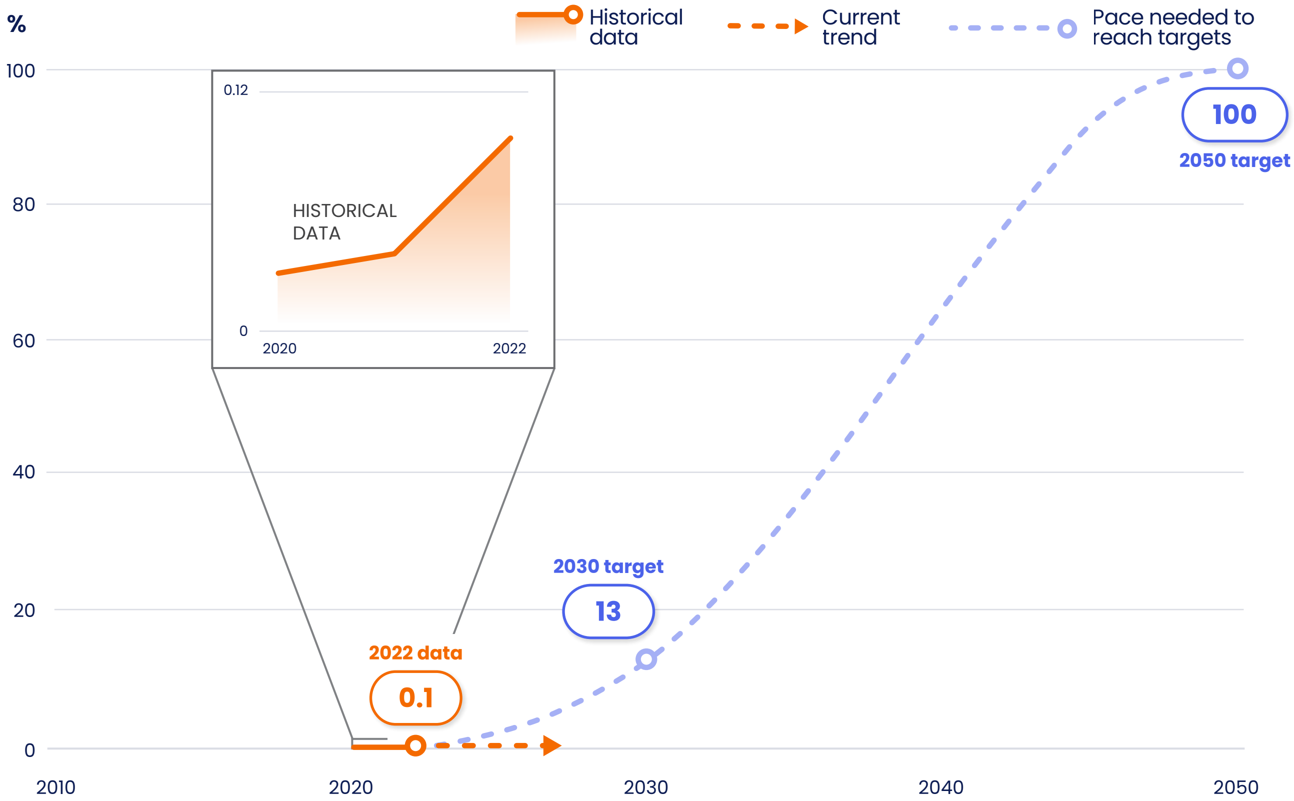
Aviation is responsible for 2 percent of global GHG emissions (Minx et al. 2021; European Commission and JRC 2022; IEA 2022i), and this share is projected to grow over the next decade under the current global policy framework (IEA 2022b). Decarbonizing aviation will be heavily dependent on a transition to sustainable aviation fuels (SAFs), which include power-to-liquid synthetic fuels and biofuels (CAT 2022d; MPP 2022a). In addition to cutting GHG emissions, switching to SAFs can also enable reduction of air pollutants such as sulfur emissions and particulate matter. Alternatives to drop-in fuels, such as powering planes with batteries or hydrogen, may also play some part in decarbonizing aviation. The quality of SAFs will be important, especially when considering indirect impacts. In particular, it is important to note that biofuels (particularly crop-derived fuels) can be unsustainable because they can compete with food production for water and land, lead to further challenges around food security and alter local ecosystems associated with high risk of land-use change through, for example, deforestation (Searchinger et al. 2019). Because of this, biofuels are unlikely to play a large role as SAFs. Along these lines, advanced biofuels produced from nonfood or nonfeed alternatives, such as nonfood algae or organic wastes and residues, do not compete with food production and, if developed sustainably, could contribute to the transition to low-carbon aviation. Finding a role for advanced biofuels in decarbonization will require significant, ongoing investment in research and development to reduce their cost, bring them to scale, and ensure that they are produced responsibly and sustainably (IRENA 2019). Comparatively, synthetic fuels have a higher scaling-up potential and greater sustainability when produced with renewable energy sources (Micheli et al. 2022).

Battery electric planes are also in development, but batteries are currently only suitable for very short-haul flights because they are heavy and many batteries are needed to provide the energy needed to move a plane long distances (Gray et al. 2021). Over those short distances, the sustainable alternative may be traveling by train where this infrastructure exists (Graver et al. 2022). For example, in China, the growth of high-speed rail enabled a modal shift away from short-haul domestic flights, resulting in an 18 percent reduction in CO_2 emissions in recent years (Strauss et al. 2021). The share of SAFs in the aviation industry remained low in 2022, accounting for 0.1 percent of the total aviation fuel consumption (Figure 40). While there are no guarantees, the rate of change will likely be nonlinear in the future. Global progress made toward this near-term target is well off track. The technology is nascent and remains in the emergence stage of an S-curve, so the share would have to double every year in order to meet the 2030 target.

FIGURE 40 | Historical progress toward 2030 and 2050 targets for share of sustainable aviation fuels in global aviation fuel supply

✕ **Right Direction, Well Off Track**

S-Curve Likely



Note: For indicators categorized as S-curve likely, acceleration factors calculated using a linear trendline are not presented, as they would not accurately reflect an S-curve trajectory. The category of progress was determined based on author judgment, using multiple lines of evidence, including a review of the literature and consultations with experts. More specifically, this indicator is categorized as well off track because it is a new technology that is still in the emergence stage of an S-curve. We do not have sufficient historical data to fit an S-curve to the data to create the current trend line, so we reverted to a linear trendline. Due to data limitations, the linear trendline was estimated using data points from only three years. This current trend line is likely too conservative, given that it does not account for the possibility of nonlinear growth. See Appendix C and Jaeger et al. (2023) for more information on methods for selecting targets, indicators, and datasets, as well as our approach for assessing progress.

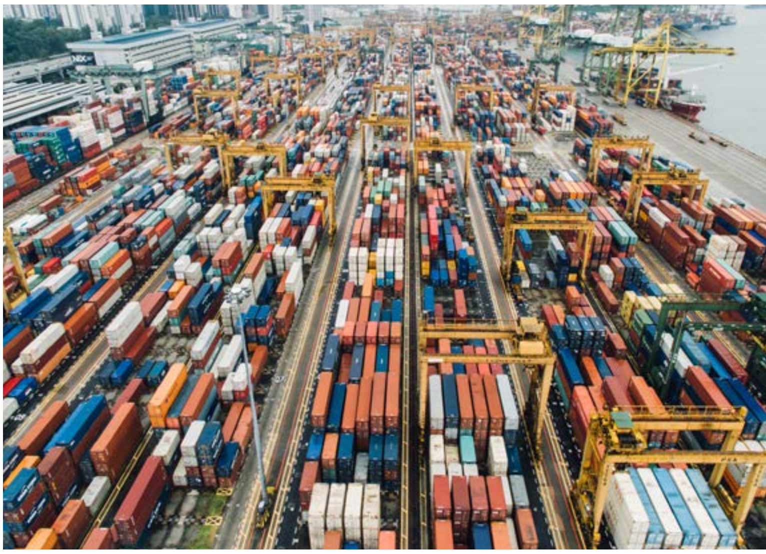
Sources: Historical data from Air Transport Action Group (2021); Mistry (2022); and IATA (2022). Targets from MPP (2022d).

Barriers currently limiting the uptake of SAFs involve production, infrastructure, policy, and the availability of different fuel technologies on aircraft. The costs of developing and producing SAFs are high in the early stages, which can be three to six times more expensive than conventional jet fuel (IRENA 2021a). Major investments will need to be made in infrastructure and training to handle and store these new fuels. At the same time, policy mechanisms are needed to further aid in removing barriers to SAF scale-up. Market-based measures would be an important tool to make SAFs cost-competitive with conventional high-emission jet fuels if the price of carbon is appropriately set. While the European Union has already introduced aviation in its emissions trading scheme since 2012, this has done little to cut emissions because of poor design that allowed free allocation of carbon credits and made credits cheap for airline companies to purchase (Transport and Environment n.d.).

From the policy side, a central challenge is that aviation is largely an international industry with no one government able to influence the entire sector. Instead, governments must build consensus through the International Civil Aviation Organization (ICAO). This is a lengthy and slow process, which to date has failed to set concrete SAF targets and policies to promote demand for SAFs in international aviation. In addition to increasing the share of SAFs in the fuel mix, governments should reduce short-haul flights and facilitate a shift to other modes of transport, such as low- or zero-emissions high-speed rail. While this may also increase road transport, this transition must happen alongside the electrification of vehicle fleets (CAT 2022d). The emission intensity per passenger-kilometer (pkm) of rail travel is 22.35g/CO_2e/pkm, almost six times lower than the 123gCO_2e/pkm emitted by plane travel (IEA 2023h).

Lately, private aviation, and its uncontrolled emissions, has been garnering more attention. Per passenger, private jets are 14 times more polluting than commercial planes, and short flights are less fuel efficient. Yet a small group of individuals continue to travel short distances by private jet when lower-carbon options are easily available (Saner 2023). The increased use of high-emission private aviation will make decarbonization more difficult and bring equity and fairness concerns into sharper relief.

In order, the largest share of aviation-related emissions (based on departing passenger flights) come from the United States, the European Union, China, and the United Kingdom (Graver et al. 2020). Apart from China, all of these top four emitters have pledged to reduce their aviation emissions. The United Kingdom, for example, has committed to a quota of 10 percent SAF by 2030, while the European Union's new ReFuelEU regulation sets a preliminary target of 6 percent by 2030 (in which biofuels are included with limitations on crop-based biofuels), and 70 percent by 2050. Additionally, there is a mandate that power-to-liquid and e-fuels make up 1.2 percent of fuel use by 2030 and 35 percent by 2050 (EASA 2022; IATA 2023). While this is a step in the right direction, stronger commitments are still needed.



TRANSPORT INDICATOR 10:
Share of zero-emissions fuels in maritime shipping fuel supply (%)

- **Targets:** The share of zero-emissions fuels (ZEFs) in maritime shipping fuel supply reaches 5 percent by 2030 and 93 percent by 2050.

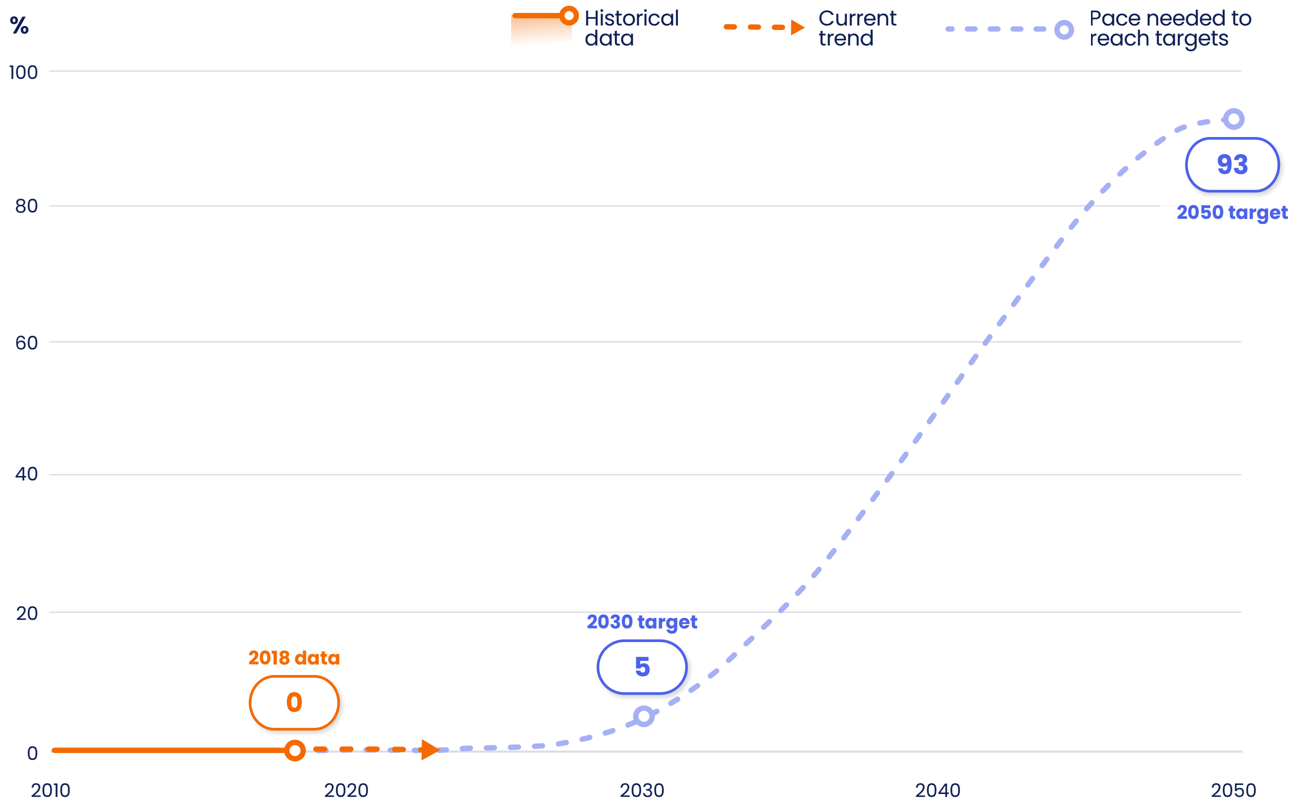
International and domestic maritime shipping accounts for 2 percent of global GHG emissions, roughly equivalent to Germany's total emissions (Minx et al. 2021; European Commission and JRC 2022; IEA 2022i). Transitioning the global maritime sector will require new zero-emissions fuels, as well as other investments beyond the fuels themselves, including new technologies to retrofit vessels to run on ZEFs. Also needed will be efforts to maximize energy efficiency, adapt port infrastructure to supply ZEFs to fleets, and develop new policy measures to support this shift (GMF 2022).

ZEFs include green ammonia, green hydrogen, e-methanol, and synthetic e-fuels produced from renewable sources of energy.[51] E-methanol and synthetic fuels made with renewable electricity still release some CO_2 when combusted, so, to produce net-zero emissions, some CO_2 used to synthesize these fuels will also need to be captured from the atmosphere (GMF 2022). While batteries are also a zero-emissions option, their relatively low energy density makes them unsuitable for long-distance shipping but can contribute to decarbonizing shorter domestic voyages (Kersey et al. 2022). The transition of the shipping sector will rely heavily on the

FIGURE 41 | Historical progress toward 2030 and 2050 targets for share of zero-emissions fuels in maritime shipping fuel supply

☒ **Right Direction, Well Off Track**

S-Curve Likely



Note: For indicators categorized as S-curve likely, acceleration factors calculated using a linear trendline are not presented, as they would not accurately reflect an S-curve trajectory. The category of progress was determined based on author judgment, using multiple lines of evidence. More specifically, this indicator is categorized as well off track, because it is a new technology that is still in the emergence stage of an S-curve. Our categorization of progress for this indicator is based on a review of the literature and consultations with experts. See Appendix C and Jaeger et al. (2023) for more information on methods for selecting targets, indicators, and datasets, as well as our approach for assessing progress.

Sources: Historical data from IMO (2020); targets from UMAS (2021).

progress made in other sectors—primarily the scaling up of renewable energy that will drive the uptake of green hydrogen and ammonia (Cames et al. 2021).

The initial high cost of alternative fuels could disproportionately affect lower-income developing countries with high climate risk. Many countries that face food insecurity, sea level rise, and extreme weather events also depend on shipping for key imports. And many of them lack the finances and capacity to transition their infrastructure, fuel supply, logistics, and labor force for new zero-emissions fuels. Ensuring a just and equitable transition in the maritime space will revolve around international cooperation on finance and capacity building. A just transition in shipping would support seafarers with the necessary skills, employment, and safety around new zero-emissions fuels and technologies, while an equitable transition would ensure that the burden of climate impacts and costs of decarbonizing the shipping sector were not disproportionally exacerbated for vulnerable countries. With a global maritime market-based measure that puts a price on GHG emissions from international shipping, it would be beneficial to distribute revenues to vulnerable and disproportionately impacted countries to support a global equitable transition (Baresic et al. 2022; Psaraftis et al. 2021).

As of 2021 the global share of ZEFs in shipping remained close to 0 percent. The uptake of green ammonia and green hydrogen, and construction of zero-emissions ships capable of running on such fuels, remained in their infancy (Figure 41). Currently, ammonia engines are expected to be commercially ready by 2025, while hydrogen engines already exist and other demonstration projects are underway, with a noticeable uptick of the latter appearing on today’s orderbooks for new ships. To keep the world in line with a 1.5-degree scenario, the share of these fuels should reach 5 percent by 2030. It should be noted that the 5 percent target (UMAS 2021) considers only ZEFs and not biofuels (for a discussion of the sustainability of biofuels, see Indicator 9). To put the 5 percent ZEF target in context, 5 percent of the fuel mix could be equivalent to a volume of 29.8 Mt of ammonia or 28.1 Mt of methanol derived from green hydrogen sources (DNV 2022).

With supportive policies, such as carbon pricing or ZEF use mandates, ZEFs' share in shipping fuels could increase rapidly and nonlinearly, with adoption rates following an S-curve trajectory of change. But because hydrogen and ammonia technology are nascent and remain at nearly zero, global progress made toward this near-term target remains well off track. It should be noted that there are signs that the market for these fuels is developing, including orders for ships to run on carbon-neutral methanol and partnerships to design ships that run on ammonia (High-Level Champions 2023).

The International Maritime Organization (IMO) is the regulatory body that would need to create the policy framework for decarbonizing maritime shipping. Historically, the pace at which the IMO has been moving toward a global consensus on effective decarbonization has been far slower than needed to achieve a 1.5°C scenario. However, a recent decision from the body has significantly accelerated progress (see more in "Recent developments across the transport sector" below). To accomplish that goal, countries will need to establish a global, market-based mechanism for imposing a price on conventional carbon-intensive fossil fuels and make ZEFs cost-competitive with them (Dominioni and Englert 2022; Psaraftis et al. 2021; Smith et al. 2022).

Recent developments across transport

There have not been any large-scale recent developments in shifting to shared, collective, or active transport. Because of the small geographic scale at which investments in shared, collective, or active transport are typically made (e.g., at the city level), any recent developments identified have largely been local in scale (see, for example, the build-out of bike lanes in Bogotá in Box 11). There have, however, been quite a few recent developments in electric light- and heavy-duty vehicles, as well as new policy tools to decarbonize aviation and shipping.

In 2022, the price of the lithium-ion battery that makes up 30–60 percent of an EV's price (Jones 2022) increased for the first time since 2010 (BloombergNEF 2022b). This increase is expected to be short-lived. It was due to supply chain constraints, especially in lithium, which are expected to ease in 2024 (BloombergNEF 2022b). Cheaper batteries are making EVs more affordable: as of 2022, a conventional gasoline-powered car in the United States cost approximately $30,000, while the average EV cost closer to $40,000 (Slowik et al. 2022). Once the decline in battery prices resumes, EV costs should also fall further, reaching purchase price parity with gasoline-powered counterparts around 2030–35 (Slowik et al. 2022).

In the United States, the Inflation Reduction Act provides revamped subsidies for light-duty electric vehicles in ways that exclude luxury EVs and the highest-income earners. The law provided a $7,500 tax credit for the purchase of new EVs (cars, vans, and sport utility vehicles) and $4,000 for used EVs (Hawkins 2022). To get this credit, the vehicle must be assembled in North America, the minerals for the battery must have been at least partially extracted in North America, the battery must have been at least partially assembled in North America, the vehicle must cost less than $80,000, and the purchaser must make less than $150,000–$300,000 depending on how they file their taxes (IRS 2023; U.S. Department of Treasury 2022). Because of these rules, only 33 of the 73 available battery electric vehicle or plug-in hybrid electric vehicle models available in the United States qualify for at least partial credit (EVAdoption 2023; U.S. DOE and U.S. EPA 2023).

At COP27 in 2022, 10 countries (Aruba, Belgium, Croatia, Curaçao, Dominican Republic, Ireland, Liechtenstein, Lithuania, Ukraine, and the United States) signed a nonbinding agreement that they would aim to sell only zero-emissions medium- and heavy-duty vehicles by 2040 (Drive to Zero 2022). More recently, the United States proposed stringent new emissions standards for cars and trucks that are designed to ensure that two-thirds of passenger car sales and a quarter of heavy-duty truck sales in the United States are electric by 2032 (Davenport 2023).

In addition to EVs, there has been recent progress in efforts to decarbonize aviation. In October 2022, at its 41st Assembly, the International Civil Aviation Organization adopted a long-term aspirational goal of reaching net-zero carbon emissions by 2050. This does not, however, subject states to any legally binding commitments (ICAO 2023). Additionally, ICAO's scenarios do not reach net-zero emissions in 2050 and do not cover aviation's crucial non-CO_2 emissions (Cardama et al. 2023). At a regional level (EASA 2022), the European Union has concluded negotiating the ReFuelEU regulation, which sets a preliminary target of 6 percent by 2030 (in which biofuels are included with limitations on crop-based biofuels), and 70 percent by 2050. Additionally, it sets a fuel mandate of 1.2 percent by 2030 and 35 percent by 2050 for power to liquid and e-fuels (EASA 2022; IATA 2023). While this is a step in the right direction, stronger commitments are still needed.

In the United States, the recent adoption of the Inflation Reduction Act introduced tax credits for SAF producers to incentivize more production. Unfortunately, these tax credits reward fuels with 50 percent emission reductions against conventional jet fuels, which falls short of the kinds of transformative fuels ultimately needed to decarbonize aviation (Sullivan 2023).

Several airlines have announced new SAF purchase agreements and set targets to use SAFs by 2030 and beyond. In 2022, 42 SAF offtake agreements were signed, amounting to almost 22,000 million liters per year (ICAO 2022). Because these are future commitments, these volumes are not yet reflected in the historical data.

Finally, in maritime shipping, a major policy development has the potential to accelerate progress. In July 2023, at the 80th session of the IMO's Marine Environment Protection Committee, member governments agreed to a revised GHG reduction strategy that updated the body's targets, including a net-zero target "by or around" 2050. It has expanded the coverage of emissions to all GHGs (not only CO_2) and covers the full life-cycle ("well to wake") emissions. It also sets a new SAF share mandate of 5 percent while striving for 10 percent zero- or "near-zero-" emissions fuels and technology by 2030. While this is a step in the right direction and in line with what benchmarks stated in this report require, the "near-zero" emissions fuels can include liquefied natural gas (LNG), which is still a fossil fuel that could persist in the fuel mix beyond 2050 (Smith and Shaw 2023). Given the long lifespan of vessels (approximately 30 years), widespread LNG use as a shipping fuel would take market share for a carbon-emitting fuel and delay the penetration of zero-emissions fuels. Avoiding continued investments, policies, and planning around the uptake of fossil fuels, especially avoiding LNG and alternative fuels not sourced from renewable energy and/or captured CO_2, will be crucial in this decade. The IMO's Energy Efficiency Existing Ship Index and Carbon Intensity Index also came into force on January 1, 2023. These IMO measures will aim to track and rate energy efficiency and carbon intensity, respectively, and require them to improve over time.

Another step forward would be to set up green shipping corridors, international projects in which several stakeholders from industry and government work together across continents to develop specific routes with the supportive conditions for zero-emissions shipping. More than 20 initiatives are underway to develop these corridors (GMF 2022).

In 2023, the European Union unveiled several sweeping proposals to include maritime shipping in its Emissions Trading System and put in place regulations called FuelEU Maritime and the Revised Renewable Energy Directive to accelerate the uptake of "zero- and low-carbon" fuels. Unfortunately, these regulations allow for biofuels (from unsustainable feedstocks) and LNG, which will make climate targets more difficult to reach. Policymakers and industry stakeholders have sought the incremental approach of encouraging fuels that are lower-carbon but still carbon-intensive, such as LNG, as part of the transition away from oil products. However, this would represent a major lock-in of investment in fossil fuels (UMAS 2021).

SECTION 6

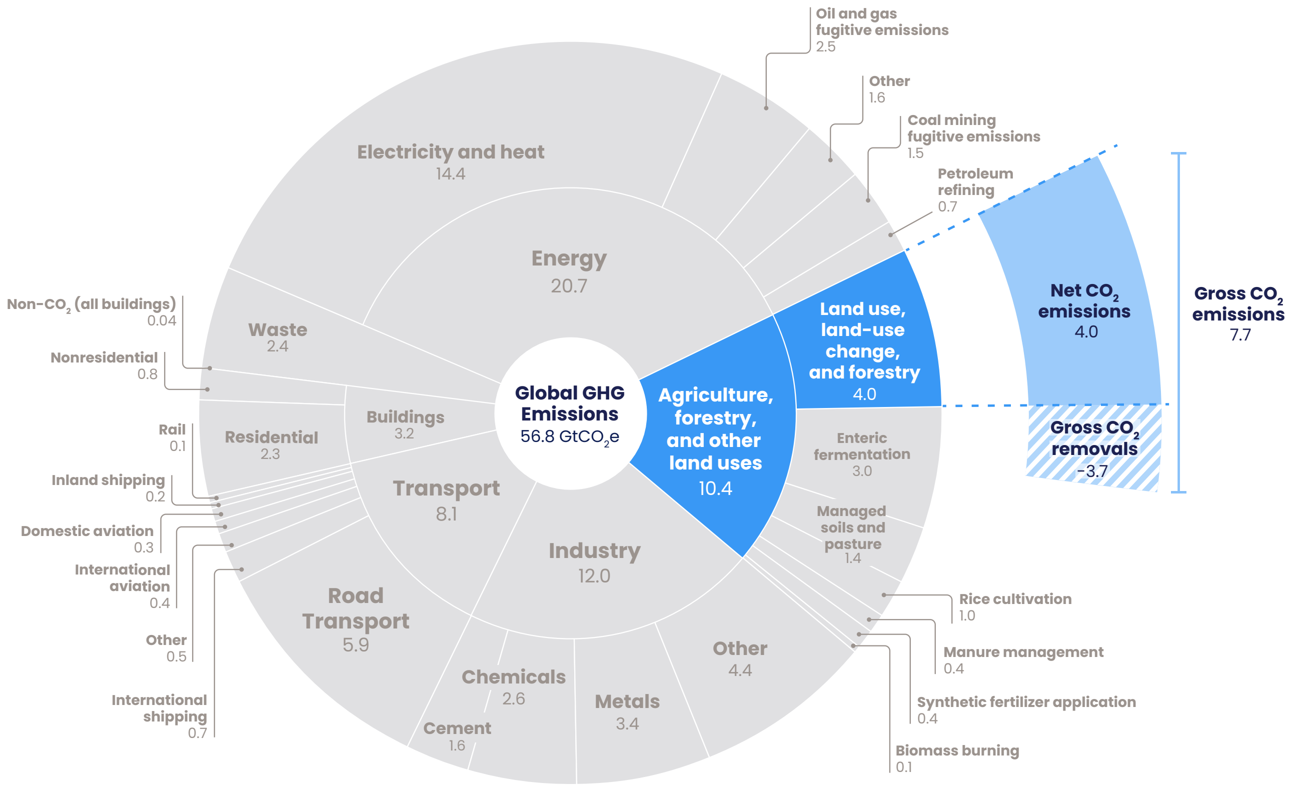
Forests and Land

Nature contributes vital, sometimes irreplaceable services to humanity that range widely, from regulating water quality to provisioning food to sustaining clean air (IPCC 2019, 2022b; IPBES 2019; UNCCD 2017).[52] Yet how people interact with the natural world also influences the climate system. The loss and degradation of ecosystems—particularly forests, peatlands, coastal wetlands, and grasslands—release GHGs into the atmosphere, while protecting, restoring, and sustainably managing these same high-carbon ecosystems can lower GHG emissions, enhance carbon sequestration, and build resilience to climate impacts (IPCC 2019, 2022b).

Agriculture, forestry, and other land uses (AFOLU) accounted for nearly one-fifth of net anthropogenic GHG emissions globally in 2021 (Figure 42),[53] with these emissions remaining relatively constant at an average of about 11 $GtCO_2e$ per year over this past decade (Minx et al. 2021; European Commission and JRC 2022). Net CO_2 emissions, which primarily stem from land use, land-use change, and forestry, accounted for roughly 40–45 percent of all net anthropogenic GHG emissions from AFOLU during this decade,[54] while methane (CH_4) and nitrous oxide (N_2O) emissions, driven predominately by agriculture, comprised the remaining 55–60 percent of these sectoral emissions (Minx et al. 2021; European Commission and JRC 2022).

Determining specific trends in net anthropogenic CO_2 emissions from land use, land-use, change, and forestry with confidence, however, remains challenging due to limitations in nationally reported data, incomplete representations of land management practices across global models, and differences in how methods conceptualize the "anthropogenic" CO_2 flux occurring across land. Until recently, some approaches, such as the average from three global bookkeeping models used in the "Global Carbon Budget," indicated a slight increase in net CO_2 emissions since 2000, while others that rely on nationally reported data, such as National Greenhouse Gas Inventories and FAOSTAT, suggested the opposite trend (IPCC 2022b). But following significant updates to the data underpinning these global bookkeeping

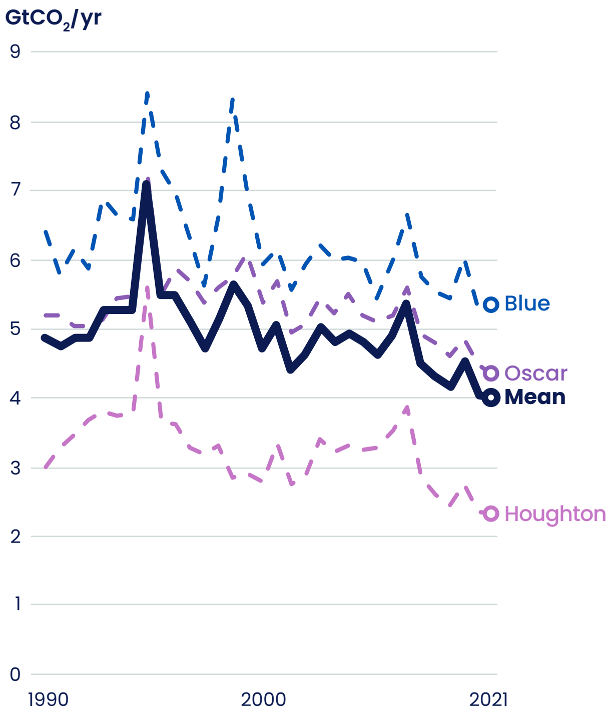
FIGURE 42 | AFOLU's contribution to global net anthropogenic GHG emissions in 2021



Notes: AFOLU = agriculture, forestry, and other land uses; CO_2 = carbon dioxide; GHG = greenhouse gas; $GtCO_2e$ = gigatonnes of carbon dioxide equivalent.

Sources: Minx et al. (2021); European Commission and JRC (2022), using CO_2 emissions data for land use, land-use change, and forestry from the three bookkeeping models in the "Global Carbon Budget 2022" (Friedlingstein et al. 2022b).

FIGURE 43 | Global net anthropogenic CO_2 emissions from land use, land-use change, and forestry



Notes: CO_2 = carbon dioxide; $GtCO_2$/yr = gigatonnes of carbon dioxide per year. Blue, Houghton, and Oscar are three separate book-keeping models that have been averaged to provide a global mean estimate.

Sources: Minx et al. (2021); and European Commission and JRC (2022), using CO_2 emissions data for land use, land-use change, and forestry from the three bookkeeping models in the "Global Carbon Budget 2022" (Friedlingstein et al. 2022b).

models, which occurred after the literature cut-off date of IPCC (2022b), the "Global Carbon Budget" revised its estimates of net anthropogenic CO_2 emissions from land use, land-use change, and forestry downward (Friedlingstein et al. 2022a), and all three global bookkeeping models now show small decreases in net anthropogenic CO_2 emissions from land use, land-use change, and forestry since the 1990s (Friedlingstein et al. 2022b) (Figure 43). Although nearly all approaches—global bookkeeping models, National Greenhouse Gas Inventories, and FAOSTAT—now suggest a decline in these net anthropogenic CO_2 emissions in recent decades, uncertainty in both the magnitude of this trend and the total decrease in CO_2 emissions remains.

But when considering both anthropogenic and nonanthropogenic CO_2 fluxes from land, including those associated with direct, human-caused change (e.g., deforestation), indirect, human-caused change (e.g., climate change), and natural effects (e.g., climate variability associated with El Niño and La Niña), the science is much clearer—land remains a carbon sink globally (IPCC 2022b), sequestering a net 7 $GtCO_2$ per year and a gross 11 $GtCO_2$ per year globally from 2012 to 2021 (Friedlingstein et al. 2022b). And since 1850, the land sink, which is comprised primarily of standing forests, has helped slow climate change by sequestering roughly one-third of CO_2 emissions from all human activities (Friedlingstein et al. 2022b). The effectiveness of these carbon sinks and stores, however, may decline with additional warming (Box 12).

BOX 12 | The vulnerability of natural carbon sinks and stores to climate change

Over the past six decades, the world's ocean and land sinks have slowed growth in atmospheric concentrations of CO_2 by absorbing increasing absolute amounts of these emissions every year. Scientists largely attribute this recent strengthening of the global land sink, specifically, to CO_2 fertilization—defined as the increase in plant photosynthesis and water-use efficiency in response to rising atmospheric concentrations of CO_2. While this global trend will likely continue through 2100, the proportion of CO_2 emissions that the world's land sink takes up will likely decline under a high-emissions pathway (IPCC 2021), and future disturbances, including climate impacts, may also reduce some lands' capacity to sequester and store carbon (IPCC 2022a). Across forests and peatlands, for example, rising temperatures coupled with more frequent, severe, and prolonged droughts may limit carbon uptake (IPCC 2022a), with several observational studies of intact tropical forest plots already indicating a weakening of the land sink across the Amazon from the mid-1980s to the early 2010s (Brienen et al. 2015; Hubau et al. 2020). Hubau et al. (2020), specifically, attribute these declines to greater tree mortality from rising temperatures and drought, which offset gains in productivity from CO_2 fertilization during this period.

Global temperature rise threatens not only to dampen the strength of some land sinks but also to increase carbon losses from ecosystems, with recurrent, more intense wildfires, enhanced tree mortality from drought and pest outbreaks, permafrost thaw, and peatland drying projected to drive future declines in terrestrial carbon stocks

BOX 12 | The vulnerability of natural carbon sinks and stores to climate change (continued)

(IPCC 2022a). Under scenarios with moderate to high levels of warming, for example, regional climates across Europe and Western Siberia could become unsuitably warm for maintaining almost all permafrost peatlands, which contain nearly 40 GtC, by the 2090s, with considerable losses beginning decades earlier (Fewster et al. 2022). Similarly, in the Amazon basin, the combined effects of an intensifying dry season and deforestation have already increased CO_2 emissions, with the southeastern region of the forest releasing more carbon than it sequestered over this past decade (Gatti et al. 2021). Should carbon losses from these ecosystems increase, so will the risk of exacerbating self-reinforcing feedbacks—complex processes that, essentially, spur rises in atmospheric concentrations of CO_2 that would further amplify global warming and intensify the same climate impacts to which these ecosystems' carbon stocks are vulnerable (IPCC 2022a). However, both the magnitude and timing of these feedbacks remain highly uncertain (IPCC 2021, 2022a).

In addition to spurring losses of terrestrial carbon stocks, continued warming may also push some ecosystems closer to tipping points—thresholds that, once crossed, trigger the reorganization of ecosystems into qualitatively different ones, often abruptly and sometimes irreversibly (IPCC 2021). A number of studies suggest that such an abrupt change could occur within the Amazon (e.g., Lenton et al. 2008; Steffen et al. 2018; Lovejoy and Nobre 2019; Lenton et al. 2019), and a synthesis of recently published papers finds that initial projections indicated that this humid tropical primary forest could have two tipping points—either 3–4°C of warming or deforesting roughly 40 percent of the Amazon—that, if reached, could cause substantial forest dieback (McKay et al. 2022). But when accounting for interactions between climate change and permanent forest loss, these thresholds likely fall to lower levels (McKay et al. 2022). Crossing the global warming tipping point (now estimated at 3.5°C), specifically, risks triggering a cascade of events that could lead to dieback across roughly 40 percent of world's largest humid tropical primary forest and release about 110 $GtCO_2$ (McKay et al. 2022). Although scientists have made advances in climate modeling, paleoclimatology, and observational analysis of nonlinear change in the climate system, confidence in these thresholds, as well as the severity of subsequent impacts, is low to medium, given the complex interactions between climate change, land-use change, and other factors (IPCC 2021, 2022b; McKay et al. 2022).

Notes: CO_2 = carbon dioxide; GtC = gigatonnes of carbon.

Global assessment of progress for forests and land

Delivering the Paris Agreement's mitigation goals requires immediate action to protect the world's terrestrial carbon sinks and stores, as well as a rapid scale-up in efforts to restore and sustainably manage these ecosystems. Over the next three decades, these land-based measures across forests, peatlands, coastal wetlands, and grasslands collectively can mitigate between 4.2 $GtCO_2e$ and 7.3 $GtCO_2e$ annually at up to \$100/tCO_2e (IPCC 2022b)—a range that is also roughly in line with pathways that limit warming to 1.5°C (Roe et al. 2019).[55] When implemented appropriately, these same strategies can also deliver substantial benefits to adaptation, sustainable development, and biodiversity (Figure 44) (Roe et al. 2021). Yet recent progress in deploying land-based mitigation remains inadequate. None of the indicators assessed for forests, peatlands, and mangroves,[56] specifically, are on track to achieve their 2030 targets (Table 5). And due to data limitations, this global assessment excludes targets and indicators for improved forest management practices that can help reduce degradation and grassland fire management practices.

TABLE 5 | Summary of global progress toward forests and land targets

INDICATOR	MOST RECENT DATA POINT (YEAR)	2030 TARGET	2035 TARGET	2050 TARGET	LIKELIHOOD OF FOLLOWING AN S-CURVE	ACCELERATION FACTOR	STATUS
Deforestation (Mha/yr)	5.8 (2022)[a]	1.9	N/A	0.31	↗	4x[b]	✕
Peatland degradation (Mha/yr)	0.06 (annual average, 1993–2018)	0	0	0	↗	Insufficient data	?
Mangrove loss (ha/yr)	32,000 (annual average, 2017–19)[c]	4,900	N/A	N/A	↗	N/A; U-turn needed[d]	⮌
Reforestation (total Mha)	130 (total gain, 2000–2020)	100 (2020–30)[e]	150 (2020–35)[e]	300 (2020–50)[e]	↗	1.5x[f]	!
Peatland restoration (total Mha)	0 (as of 2015)[g]	15 (2020–30)[e]	N/A	20–29 (2020–50)[e]	↗	Insufficient data	?
Mangrove restoration (total ha)	15,000 (total direct gain, 1999–2019)[h]	240,000 (2020–30)[e]	N/A	N/A	↗	>10x[i]	✕

Notes: ha/yr = hectares per year; Mha/yr = million hectares per year. Historical data for forests and land indicators were estimated using maps derived from remotely sensed data, and accordingly, they contain a degree of uncertainty. See Jaeger et al. (2023) for more information on methods for selecting targets, indicators (including the known limitations of each), and datasets, as well as our approach for assessing progress.

[a] See Jaeger et al. (2023) and Box 5 in Boehm et al. (2022) for a description of methods used to estimate deforestation.

[b] Indicators for forests and land experience high interannual variability in historical data due to both anthropogenic and natural causes. Accordingly, 10 years instead of 5 years was used to calculate the linear trendline where possible. For this indicator, however, an 8-year trendline was calculated, using data from 2015 to 2022 due to temporal inconsistencies in the data before and after 2015 (Weisse and Potapov 2021).

[c] Historical data from Murray et al. (2022), which estimated gross mangrove area lost from 1999 to 2019, was broken into three-year epochs. Loss for each epoch was divided by the number of years in the epoch to determine the average annual loss rate.

[d] Indicators for forests and land experience high interannual variability in historical data due to both anthropogenic and natural causes. Accordingly, 10 years instead of 5 years was used to calculate the linear trendline where possible. For this indicator, however, a 12-year trendline was calculated, using data from 2008 to 2019 to account for the full range of years included in four 3-year epochs from Murray et al. (2022). To estimate the average annual loss rate from 2008 to 2019, gross loss was divided by the number of years in each epoch.

[e] Reforestation, peatland restoration, and mangrove restoration targets are additional to any reforestation and restoration that occurred prior to 2020, and these targets are cumulative from either 2020 to 2030 or 2020 to 2050.

[f] Following Boehm et al. (2021) and due to data limitations, the average annual rate of change across the most recently available time period (2000–2020) was used to estimate the historical rate of change, rather than a linear trendline.

[g] Peatland restoration targets were adapted from Humpenöder et al. (2020) and Roe et al. (2021), which assume that 0 Mha of peatlands globally were rewetted as of 2015. This assumption, however, does not suggest that peatland restoration has not occurred, as there is evidence of rewetting, for example, in Canada, Indonesia, and Russia (UNEP 2022b; Sirin 2022; BRGM 2023), but rather speaks to the lack of global data on peatland restoration.

[h] Murray et al. (2022) estimated that a gross area of 180,000 ha (95 percent confidence interval of 0.09 to 0.30 Mha) of mangrove gain occurred from 1999 to 2019, only 8 percent of which can be attributed to direct human activities, such as mangrove restoration or planting. We estimated the most recent data point for mangrove restoration by taking 8 percent of the total mangrove gain from 1999 to 2019 (15,000 ha). See Jaeger et al. (2023) for more information.

[i] Following Boehm et al. (2021) and due to data limitations, the average annual rate of change across the most recently available time period (1999–2019) was used to estimate the historical rate of change, rather than a linear trendline.

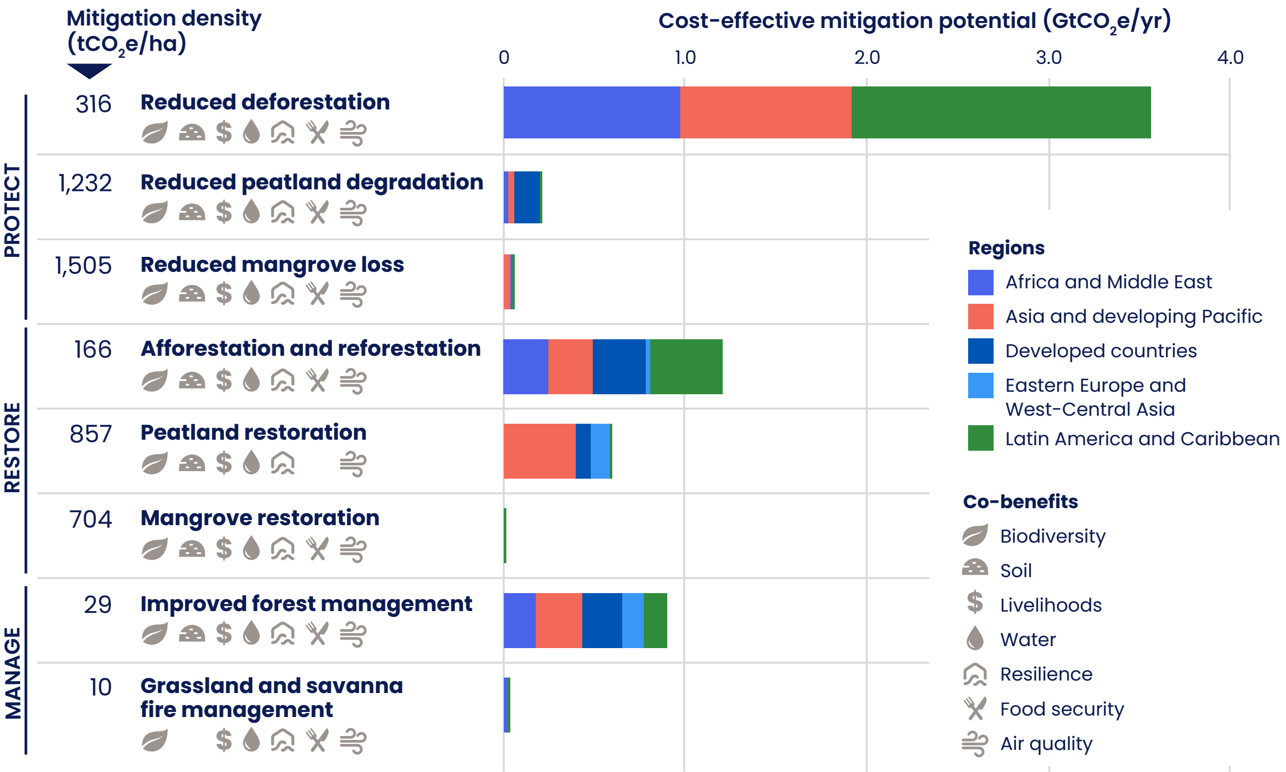
Sources: Historical data from Global Forest Watch, using datasets updated to 2022 (Hansen et al. 2013; Curtis et al. 2018; Turubanova et al. 2018; Tyukavina et al. 2022), as well as Potapov et al. (2022a); Conchedda and Tubiello (2020); Murray et al. (2022); and Humpenöder et al. (2020); targets derived from Roe et al. (2019, 2021); Humpenöder et al. (2020); and Griscom et al. (2017).

Protect forests, peatlands, and mangroves

Protecting forests, peatlands, and mangroves can generate multiple climate benefits by preventing the release of their large carbon stores into the atmosphere and by maintaining their ability to continue sequestering carbon (IPCC 2022b). Safeguarding tropical forests, in particular, can deliver additional contributions to mitigation that extend far beyond carbon, as these ecosystems sustain a range of biophysical mechanisms, such as evapotranspiration, that cool Earth's surface and near-surface air (Lawrence et al. 2022). By one estimate, accounting for this cooling effect from biophysical processes would increase the climate benefits of avoiding tropical deforestation by 50 percent, relative to the mitigation potential of reducing CO_2 emissions alone (Seymour et al. 2022). Accordingly, virtually halting deforestation, peatland degradation, and mangrove loss can contribute the lion's share of land-based mitigation needed to limit warming to 1.5° C. Even when accounting for GHG emissions reductions, alone, these measures contribute more than half of the cost-effective mitigation potential available at up to \$100/tCO_2e from land-based activities across ecosystems (Figure 44) (Roe et al. 2021).

Not only can protecting these three ecosystems deliver relatively high cost-effective mitigation benefits per hectare (Figure 44), but these land-based measures also will prove critical to near-term climate action (Cook-Patton et al. 2021). Together, the world's forests, peatlands, and mangroves hold well over 1,000 GtC in their aboveground biomass and soils (Pan et al. 2011; Temmink et al. 2022), and, by one estimate, roughly a third or less of these carbon stocks (~340 GtC) are vulnerable to human disturbances, such that they would be released into the atmosphere following conversion or degradation of these ecosystems (Noon et al. 2021). Some of these losses in carbon can occur quite rapidly, such as when large-scale commodity producers clear forested peatlands with fire; if lost, much of this carbon would be difficult for ecosystems to recover on timescales relevant to reaching net-zero CO_2 emissions by midcentury, effectively creating a permanent deficit in the world's remaining carbon budget for 1.5°C (Goldstein et al. 2020; Cook-Patton et al. 2021; Noon et al. 2021). More

FIGURE 44 | Global cost-effective mitigation potentials for land-based measures across forests, peatlands, mangroves, and grasslands from 2020 to 2050



Notes: $GtCO_2e$/yr = gigatonnes of carbon dioxide equivalent per year; tCO_2e/ha = tonnes of carbon dioxide equivalent per hectare. Following Roe et al. (2021), cost-effective mitigation potential includes reductions in GHG emissions and enhanced carbon sequestration available at carbon prices of up to \$100/tCO2e.

Source: Roe et al. (2021).

specifically, fully rebuilding these lost carbon stocks could take 6 to 10 decades for forests, well over a century for mangroves, and centuries to millennia for peatlands (Goldstein et al. 2020; Temmink et al. 2022). But despite this significant role that protecting these ecosystems can play in avoiding GHG emissions, collective efforts to virtually halt deforestation remain well off track, and, while global data are insufficient to assess progress, available evidence suggests that peatland degradation continues to occur. Worse still, though mangrove losses remain substantially lower than those observed in the late 20th century, they are once again ticking upward, such that a step-change in action is needed.

FORESTS AND LAND INDICATOR 1:
Deforestation (Mha/yr)

- **Targets:** The annual rate of gross deforestation globally declines to 1.9 million hectares per year (Mha/yr) by 2030 and to 0.31 Mha/yr by 2050.

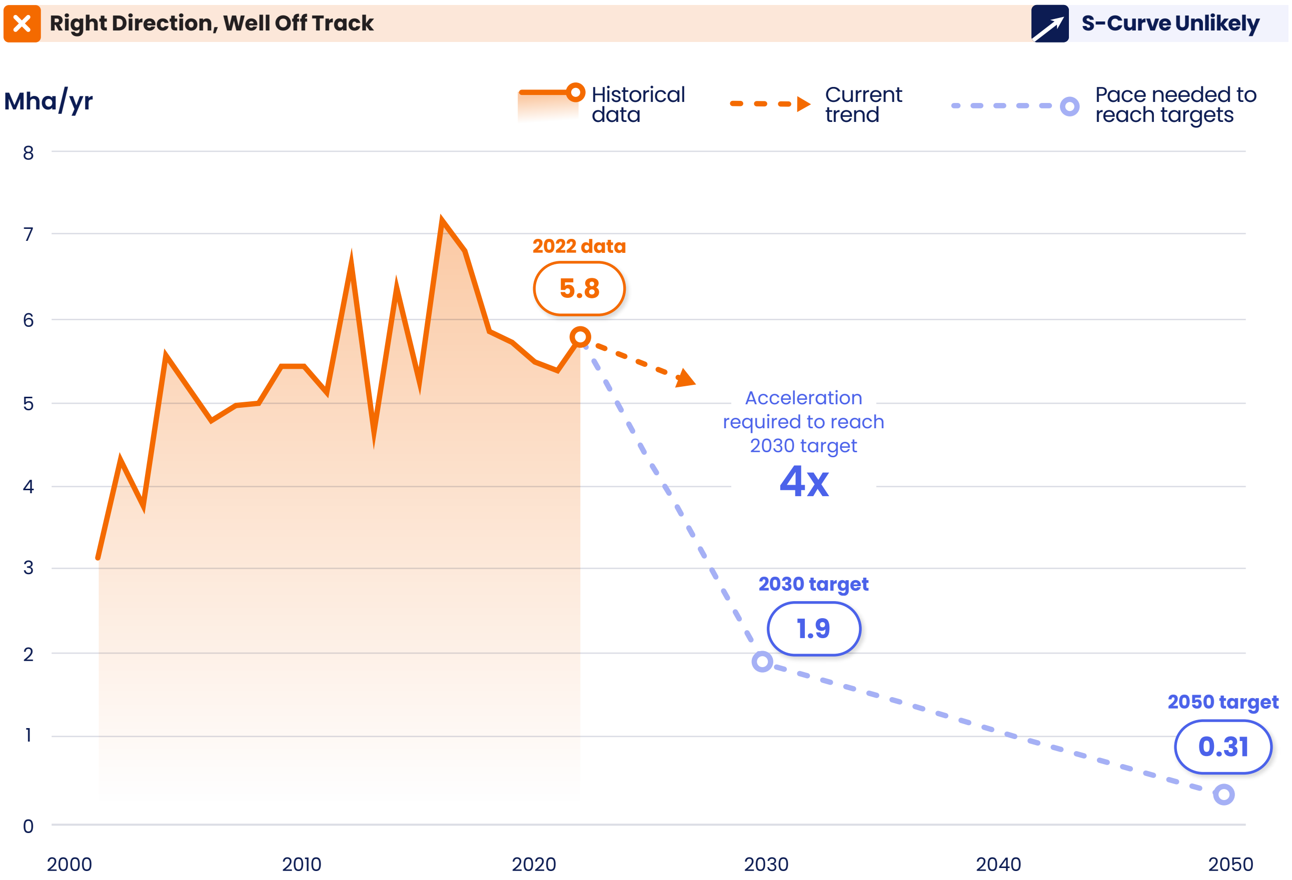
Although the world's forests remain a net carbon sink (Harris et al. 2021; Friedlingstein et al. 2022b), deforestation—driven, in large part, by agricultural expansion (Curtis et al. 2018; Pendrill et al. 2022)—remains the primary driver of emissions from land use, land use change, and forestry (Friedlingstein et al. 2022b). Limiting global temperature rise to 1.5°C, then, will require dramatic declines in permanent forest loss over the next three decades. More specifically, annual deforestation rates, as well as associated GHG emissions, need to fall 70 percent by 2030 and 95 percent by 2050, relative to 2018 levels (Roe et al. 2019), to help achieve this Paris Agreement temperature limit.

BOX 13 | How do we estimate deforestation?

To estimate historical trends in deforestation, we used a combination of four datasets available on Global Forest Watch: annual tree cover loss (Hansen et al. 2013) updated to 2022, tree cover loss by dominant driver (Curtis et al. 2018) updated to 2022, humid tropical primary forest extent (Turubanova et al. 2018), and annual tree cover loss due to fire (Tyukavina et al. 2022) updated to 2022. These estimates include tree cover loss that likely represents deforestation, defined as the permanent conversion of forest cover to new, nonforest land uses (WRI 2023e). Consequently, they include all tree cover loss (Hansen et al. 2013) within areas whose dominant driver, as defined by Curtis et al. (2018), was classified as commodity-driven deforestation and urbanization, as well as humid tropical primary forest loss (Turubanova et al. 2018) due to the expansion of shifting agriculture. We also excluded all tree cover loss due to fire (Tyukavina et al. 2022), which is likely to be more temporary in nature,[57] to better estimate trends in permanent forest conversion without the interannual variability linked to extreme weather events. Finally, we removed any areas of overlap with data on mangrove loss (Murray et al. 2022) to avoid double-counting. See Box 5 in Boehm et al. (2022) for more information.

But global efforts to achieve this near-term target remain well off track. From 2015 to 2022, for example, the world permanently lost a total of 48 million hectares (Mha) of forests, with gross GHG emissions from deforestation amounting to 28 GtCO$_2$e over this time period (see Box 13 for how we estimate deforestation) (Hansen et al. 2013; Curtis et al. 2018; Turubanova et al. 2018; Tyukavina et al. 2022; Harris et al. 2021). And while the annual rate of deforestation declined from a recent high of 7.2 Mha in 2016 to 5.4 Mha in 2021, it increased to 5.8 Mha in 2022 (Hansen et al. 2013; Curtis et al. 2018; Turubanova et al. 2018; Tyukavina et al. 2022)—a slight worsening relative to recent trends. Gross GHG emissions from permanent forest loss also rose marginally from 3.3 in 2021 to 3.6 GtCO$_2$e in 2022 (Harris et al. 2021)—roughly equivalent to India's and South Africa's combined GHG emissions in 2020 (Climate Watch 2023). But getting on track for

FIGURE 45 | Historical progress toward 2030 and 2050 targets for deforestation



Notes: Mha/yr = million hectares per year. Indicators for forests and land experience high interannual variability in historical data due to both anthropogenic and natural causes. Accordingly, 10 years instead of 5 years was used to calculate the linear trendline where possible. For this indicator, however, an 8-year trendline was calculated, using data from 2015 to 2022 due to temporal inconsistencies in the data before and after 2015 (Weisse and Potapov 2021). Also, historical data for forests and land indicators were estimated using maps derived from remotely sensed data, and accordingly, they contain a degree of uncertainty. See Jaeger et al. (2023) for more information on methods for selecting targets, indicators (including the known limitations of each), and datasets, as well as our approach for assessing progress.

Sources: Historical data from Global Forest Watch, calculated from datasets updated to 2022. Data updates are based on methods published in Hansen et al. (2013); Curtis et al. (2018); Turubanova et al. (2018); and Tyukavina et al. (2022); targets derived from Roe et al. (2019). See Jaeger et al. (2023) and Box 5 in Boehm et al. (2022) for a description of methods used to estimate deforestation.

2030 will require annual deforestation rates to decline much more rapidly—roughly four times faster over this decade (Figure 45).

Nearly 97 percent of deforestation from 2001 to 2022 occurred in the tropics (WRI 2023c), and since 2015 just three countries—Indonesia, Brazil, and the Democratic Republic of the Congo—have accounted for over half of all deforestation globally. Trends within these tropical countries, however, vary considerably. Indonesia, for example, has witnessed substantial decreases in permanent forest losses, with the annual rate of deforestation declining by an average of 6 percent per year from 2015 to 2022. But in Brazil, deforestation rates have increased by an average of 10 percent per year over this same period, reversing declines observed in the previous decade, and similarly, the Democratic Republic of the Congo saw average rates of permanent forest losses rise by an average of 7 percent per year (Hansen et al. 2013; Curtis et al. 2018; Turubanova et al. 2018; Tyukavina et al. 2022). Elsewhere in the tropics, however, a handful of countries have succeeded in protecting their forests, maintaining deforestation rates that fall well below those observed for Indonesia, Brazil, and the Democratic Republic of the Congo (Box 14).

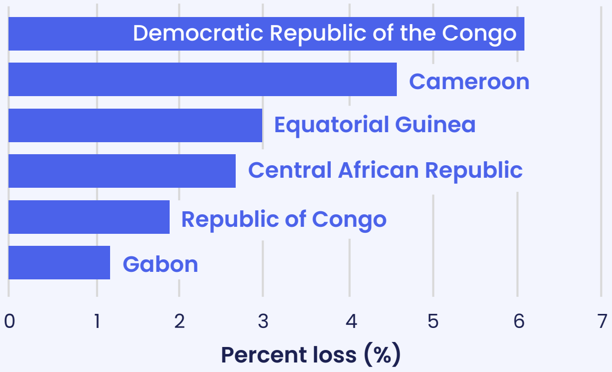
Importantly, this assessment of progress excludes forest degradation, which can reduce forests' capacity to sequester and store carbon, among other life-sustaining ecosystem services, without a change in land cover or use. But while degradation may not lead to the complete loss of forest, it remains a significant source of GHG emissions. By one estimate, logging, drought, edge effects from deforestation, and fires, together, spurred degradation across nearly 40 percent of the Amazon from 2001 to 2018, with annual carbon losses from this degradation comparable to those associated with deforestation across the basin during the same period (Lapola et al. 2023). Consequently, preventing forest

BOX 14 | Spotlight on Gabon: Protecting humid tropical primary forests in the Congo Basin

Gabon is one of the most forested countries in the world, with humid tropical primary forests stretching across more than 85 percent of its land (Hansen et al. 2013; Turubanova et al. 2018). These forests remain a carbon sink, sequestering an annual average of net 66 MtCO$_2$ from 2001 to 2022 (Harris et al. 2021), and they also provide habitat to many species, including approximately half of the remaining forest elephant population in Africa (Maisels et al. 2013). Fortunately, Gabon has maintained the lowest rate of primary forest loss (measured as a proportion of countries' primary forest area) in the Congo Basin, losing a total of just 0.27 Mha of humid tropical primary forest from 2002 to 2022 (Hansen et al. 2013; Turubanova et al. 2018) (Figure B14.1). With this historically low level of primary forest loss, Gabon is among the world's "High Forest, Low Deforestation" (HFLD) countries, and in 2021, it was the first African nation to receive a results-based payment for reducing emissions from deforestation and forest degradation (REDD+), with the initial tranche of $17 million coming from Norway as part of its $150 million commitment to Gabon under the Central African Forest Initiative (Tan 2021).

The Gabonese government has taken several steps to protect its forests, including the recent adoption of a legislative framework that demonstrates a strong political will to prioritize forest protection (Searcey 2022; Tan 2021). In 2001, for example, Gabon revised its Forest Code (Law 016/2001) to require logging companies not only to submit 30-year forest management plans for their concessions but also to adopt more sustainable practices within these forests, including low-impact harvesting techniques and a harvest rotation period of at least 20 years to enable regrowth (Forest Trends 2021; Gabonese Republic 2021). Just six years later, Gabon established 13 national parks across 3 Mha, and protected terrestrial areas now cover just over 20 percent of the country's land (Gabonese Republic 2021). And in 2018, then-president Ali Bongo Ondimba announced that, by 2022 (later adjusted to 2025), all forest concessions must be certified by the Forest Stewardship Council (FSC 2020; Collins 2022b). Additional efforts from the government to improve traceability across timber supply chains—for example, by developing a monitoring system that relies on bar codes to track individual logs—may also help support conservation and reduce illegal logging (Collins 2022b; Searcey 2022; Moballa-Mbun et al. 2023).

FIGURE B14.1 | Primary forest loss in Gabon relative to other Congo Basin countries from 2002 to 2022



Note: Primary forest loss from 2002 to 2022 is expressed as the percentage of each country's 2001 primary forest area.

Sources: Historical data from Global Forest Watch, using datasets updated to 2022 (Hansen et al. 2013; Turubanova et al. 2018).

Civil society has also helped protect Gabon's forests. Nongovernmental organizations like Conservation Justice and Brainforest, for example, have been conducting independent forest monitoring, as well as investigating and documenting illegal activities, for almost a decade. Not only has this work led to multiple arrests, but also some of these organizations have helped provide legal assistance to communities suffering from the harmful impacts of large-scale forest exploitation (Nyirenda and Mbzibain 2020; Vallée et al. 2022). Local communities, too, have led efforts to conserve the country's forests. Gabon recently witnessed the first case of a community in its northeastern region successfully requesting the government to declassify a logging concession on their territory, with the former minister of water, forests, the sea, and the environment ordering the logging company to leave. The Massaha, the local community that requested this declassification, has since formally asked the government to establish a protected area across the concession, which they would manage (Evine-Binet 2022).

But despite this strong regulatory framework and civil society's efforts, challenges persist. While Gabon recently received its first results-based REDD+ payment, accessing climate finance has proven to be especially difficult for HFLD countries (Schweikart et al. 2022), and Gabon will need considerably more financial support to maintain low deforestation rates (Republic of Gabon 2022). Relatedly, effective enforcement also remains difficult, and, while illegal logging has declined, it continues to threaten Gabon's forests

BOX 14 | Spotlight on Gabon: Protecting humid tropical primary forests in the Congo Basin

(Forest Trends 2021; Searcey 2022). Moreover, there has been criticism that Gabon's Forest Code and strict protection status of national parks does not adequately consider local communities' rights and, in some cases, threatens rural livelihoods (Yobo and Ito 2016; Wily 2012; Pyhälä et al. 2016; WRM 2020). Development and environmental projects have started to dedicate funding to support forest-dependent communities' income, livelihoods, and well-being. At the 2023 One Forest Summit, for example, 50 business leaders committed to creating 10 million jobs in sustainable forest management to benefit local communities across the tropics, including in Gabon (GEF 2022; James 2021; One Planet Summit 2023). While these developments represent welcome changes, continued conservation of Gabon's forests will require more systematic approaches to addressing these challenges.

Beyond these barriers to implementation, Gabon's ability to maintain these low rates of deforestation may also prove challenging as the world transitions away from fossil fuels, and the government tries to lift roughly a third of the Gabonese population out of poverty (World Bank 2023c). As sub-Saharan Africa's fourth-largest oil producer, the country's economy relies heavily on this fossil fuel. In 2020, for example, oil production accounted for almost 40 percent of Gabon's GDP and just over 70 percent of its exports (World Bank 2023e). To diversify its economy and safeguard it from shocks, Gabon has pledged to expand other industries, including timber and palm oil production, sustainably. The government, for example, has allocated degraded lands to industrial palm oil plantations, established rules mandating reduced-impact logging practices, and banned raw timber exports to encourage production of more valuable wood products in Gabon (Searcey 2022; Prentice 2021; Tan 2021). While it is far too soon to evaluate the environmental and climate impacts of this strategy, Gabon does offer a litmus test for synergizing economic development and forest conservation. However, following the military coup in August 2023, it remains unclear if the new government will continue implementing former president Ali Bongo's forest policies.

Notes: GDP = gross domestic product; Mha = million hectares; $MtCO_2$ = million tonnes of carbon dioxide; REDD+ = reducing emissions from deforestation and forest degradation.

degradation represents an important land-based mitigation measure, despite the challenges associated with defining and monitoring such degradation (WRI 2023a).

FORESTS AND LAND INDICATOR 2:
Peatland degradation (Mha/yr)

- **Targets:** The annual rate of peatland degradation globally declines to 0 million hectares per year (Mha/yr) by 2030, with no additional degradation from 2030 to 2050.

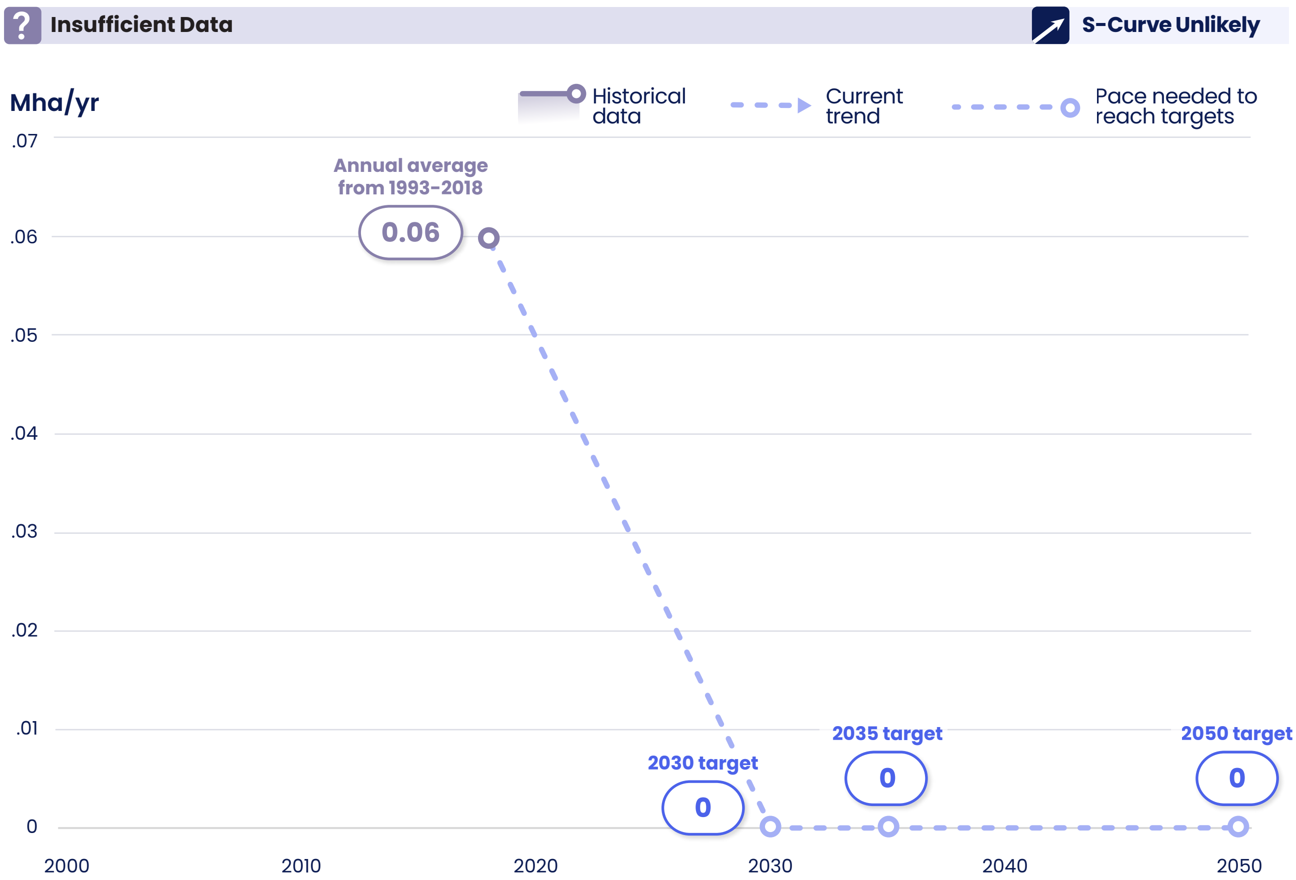
Covering just 3.8 percent of the planet's land (UNEP 2022b), peatlands—also known as mires, bogs, fens, and swamp forests—are global hotspots for carbon sequestration and long-term storage. These ecosystems contain at least a fifth of soil organic carbon stocks globally (Yu et al. 2010; Page et al. 2011; Scharlemann et al. 2014; Dargie et al. 2017) and store an order of magnitude more carbon per hectare than terrestrial forests (Temmink et al. 2022).[58] Peatlands also hold large stores of organic nitrogen (Leifeld and Menichetti 2018; Hugelius et al. 2020), as their waterlogged soils slow decomposition and allow carbon- and nitrogen-rich peat to accumulate over millennia. But when these ecosystems' water tables fall, oxygen enters the upper layers of peat, spurring decomposition and subsequent losses of stored carbon and nitrogen (FAO 2020; UNEP 2022b). These degraded peatlands can emit CO_2 and N_2O for decades to centuries until all peat is fully lost or their soils are rewetted (Wilson et al. 2016; Leifeld and Menichetti 2018; FAO 2020). Draining peatlands, in particular, increases the risk of peat fires, which can lead to additional GHG emissions (FAO 2020; UNEP 2022b).

An estimated 57 Mha—nearly 12 percent of the world's peatlands—are degrading, such that they are no longer actively forming peat, and peat accumulated over centuries to millennia is now disappearing (UNEP 2022b). While widespread land conversion, peat extraction, and peatland drainage historically occurred across boreal and temperate regions, peatland degradation is now concentrated primarily within the tropics (Leifeld et al. 2019; Fluet-Chouinard et al. 2023), where the expansion of both small-scale farming and large-scale commodity production increasingly threatens these ecosystems (Dohong et al. 2017; Page et al. 2022). More specifically, just under 5 percent of the world's boreal peatlands are degrading, but in the tropics this figure jumps to more than 40 percent (Leifeld and Menichetti 2018).

Collectively, these degraded peatlands emit about 1.9 $GtCO_2e$ each year (Leifeld and Menichetti 2018; UNEP 2022b)—roughly equivalent to Russia's GHG emissions in 2020 (Climate Watch 2023). This estimate, however, excludes GHG emissions from peat fires that, while highly variable and difficult to measure, likely occur on an order of magnitude from 0.5 to 1.0 $GtCO_2e$ annually (UNEP 2022b). Absent concerted action to protect peatlands, these GHG emissions could rise significantly, with recent studies projecting peatland degradation across another 10 to 12 Mha—areas roughly the size of South Korea and Malawi, respectively—by 2100 in business-as-usual scenarios (Leifeld et al. 2019; Humpenöder et al. 2020).

Halting worldwide peatland degradation by 2030, then, can help limit global temperature rise to 1.5°C (Griscom et al. 2017). While 177 countries contain peatlands (UNEP 2022b), Roe et al. (2021) estimate that roughly 90 percent of the cost-effective mitigation potential is concentrated among just three nations: Canada, Indonesia, and the Republic of Congo. But despite recent advances in mapping peatlands within some of these countries and globally, significant data gaps, such as incomplete coverage, inconsistent quality, and outdated data (UNEP 2022b), inhibit efforts to monitor progress toward this target. Data estimating the area of organic soils drained for agriculture, including crop cultivation and grazing (Conchedda and Tubiello 2020), provide a best available, though still imperfect, proxy (e.g., some organic soils are not peat).[59] These data show that, worldwide, 1.6 Mha of organic soils were drained for agricultural activities from 1993 to 2018, with an average rate of 0.06 Mha/yr over this time period (Conchedda and Tubiello 2020). Although these proxy data are insufficient to assess recent progress toward this near-term target, they indicate that degradation of the world's peatlands continues (Figure 46).

FIGURE 46 | Historical progress toward 2030, 2035, and 2050 targets for peatland degradation



Notes: Mha/yr = million hectares per year. Historical data for forests and land indicators were estimated using maps derived from remotely sensed data, and accordingly, they contain a degree of uncertainty. See Jaeger et al. (2023) for more information on methods for selecting targets, indicators (including the known limitations of each), and datasets, as well as our approach for assessing progress.

Sources: Historical data from Conchedda and Tubiello (2020); targets derived from Griscom et al. (2017).

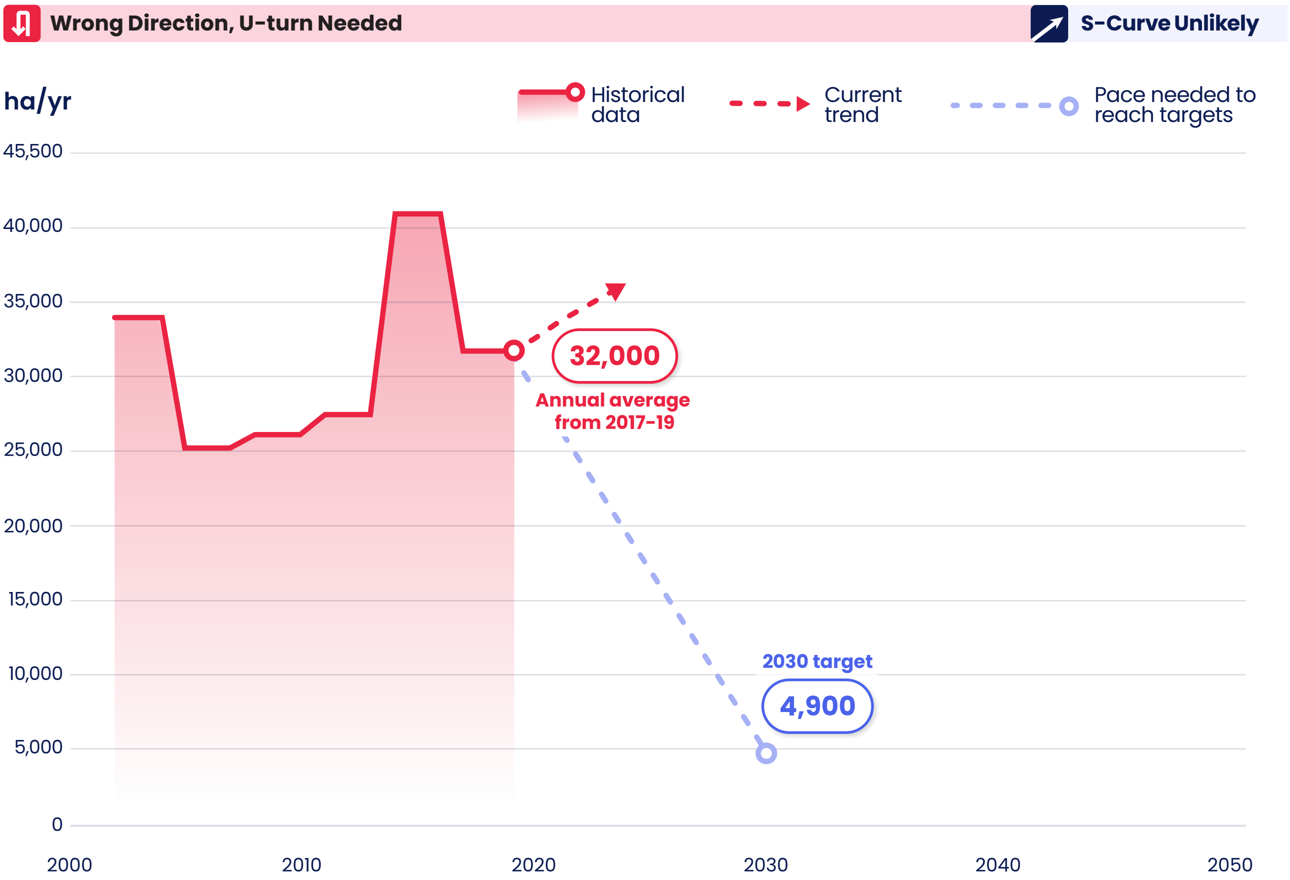
These proxy data, however, may underestimate peat degradation for several reasons. The data focus on drainage of organic soils solely for agricultural activities, and although agriculture remains a primary driver of peatland degradation globally, other causes of degradation—including road and infrastructure development, forestry, oil sands mining, and peat extraction, among others—are not included in the estimates (Conchedda and Tubiello 2020; UNEP 2022b). Moreover, the threshold of peat depth used to define peatlands varies by country. In nations where this threshold is lower than the depth of organic material used to define organic soil in Conchedda and Tubiello (2020), peatland degradation may not be included in these estimates of drained organic soils. As a result, the global extent of organic soils is significantly lower than the most recent estimates for peatland area (Xu et al. 2018; UNEP 2022b), and estimates of the area of organic soils drained for agricultural activities (25 Mha) are substantially lower than the most recent estimate of the global area of degraded peatland (57 Mha) (Conchedda and Tubiello 2020; UNEP 2022b).

FORESTS AND LAND INDICATOR 3:
Mangrove loss (ha/yr)

- **Target:** The annual rate of gross mangrove loss globally declines to 4,900 hectares per year (ha/yr) by 2030.[60]

Stretching across nearly 15 Mha of shoreline globally (Bunting et al. 2022), mangrove forests are among the world's most carbon-dense ecosystems (Alongi 2014; Spalding and Leal 2021), holding at least twice as much carbon per hectare as boreal, temperate, and tropical forests (Goldstein et al. 2020; Temmink et al. 2022).[61] Globally, mangroves forests store approximately 6.2 to 15.2 GtC, with over 80 percent of this carbon contained in their soils (Goldstein et al. 2020; Leal and Spalding 2022; Temmink et al. 2022).[62] Accumulation of carbon in these coastal wetland soils occurs gradually over hundreds to thousands of years, as mangrove roots trap suspended organic matter during tidal flooding and as dead biomass slowly decomposes in their waterlogged soils (Leal and Spalding 2022). Due to these ecosystems' carbon

FIGURE 47 | Historical progress toward 2030 target for mangrove loss



Notes: ha/yr = hectares per year. Indicators for forests and land experience high interannual variability in historical data due to both anthropogenic and natural causes. Accordingly, 10 years instead of 5 years was used to calculate the linear trendline where possible. For this indicator, however, a 12-year trendline was calculated, using data from 2008 to 2019 to account for the full range of years included in four 3-year epochs from Murray et al. (2022). To estimate the average annual loss rate from 2008 to 2019, gross loss was divided by the number of years in each epoch. Also, historical data for forests and land indicators were estimated using maps derived from remotely sensed data, and, accordingly, they contain a degree of uncertainty. See Jaeger et al. (2023) for more information on methods for selecting targets, indicators (including the known limitations of each), and datasets, as well as our approach for assessing progress.

Sources: Historical data from Murray et al. (2022); 2030 target derived from Roe et al. (2021).

density, the loss of even a small area of mangroves, particularly when their soils are disturbed or dredged, can release an outsized amount of GHG emissions, relative to other ecosystems.

Although average annual rates of global gross mangrove loss have slowed dramatically since the late 20th century (Friess et al. 2019), they appear to once again be ticking upward.[63] From 1999 to 2019, for example, the world lost an estimated 560,000 hectares (ha) of mangrove forests,[64] with gross losses of these coastal wetlands increasing by an average of nearly 950 hectares per year (ha/yr) since 2008 (Murray et al. 2022). Accordingly, global efforts to virtually halt conversion of mangrove forests have fallen short, such that recent rates of change are heading in the wrong direction entirely, and a sharp reversal in action is needed to reduce these losses to no more than 4,900 ha/yr by 2030 to help limit warming to 1.5°C (Figure 47) (Roe et al. 2021).

Asia has experienced the largest mangrove losses over the past few decades (Bunting et al. 2022; Murray et al. 2022). Home to roughly 20 percent of the world's mangrove forests (Bunting et al. 2022), Indonesia lost more of these coastal wetlands than any other country between 1999 and 2019, accounting for roughly a third of mangrove losses globally (Murray et al. 2022). However, there are some signs of progress across this Southeast Asian nation. Annual rates of mangrove loss, for example, declined from an average of approximately 15,000 ha/yr from 2014 to 2016 to an average of 10,000 ha/yr from 2017 to 2019. Still, these most recent rates of loss remain well above those from 2005 to 2013, indicating the need for more rapid declines (Murray et al. 2022). Myanmar and Brazil have also experienced relatively high rates of mangrove loss; together with Indonesia, these three countries accounted for approximately half of global mangrove losses from 1999 to 2019 (Murray et al. 2022).

These estimates of mangrove loss include those directly attributable to human activities, such as conversion to aquaculture ponds, rice paddies, or palm oil plantations, as well as those due to indirect anthropogenic causes like sea level rise and more natural processes like coastal erosion or tropical storms (Murray et al. 2022). Globally, losses stemming from the latter account 50 percent of mangrove losses, though this share can vary significantly by region. In Asia, for example, mangrove losses that are directly attributable to human activities account for 75 percent of losses (Murray et al. 2022). Ongoing changes, including losses, then, can be expected due to these ecosystems' dynamic nature, and when considering both losses and gains—or the net change in mangrove extent—global estimates indicate that the annual rate of net losses has decreased over the past two decades (Bunting et al. 2022).

Restore forests, peatlands, and mangroves

Limiting global warming to 1.5°C will also require large-scale restoration of high-carbon ecosystems (Roe et al. 2019). Reestablishing forests, peatlands, and mangroves, specifically, can deliver almost 30 percent of the cost-effective mitigation potential from land-based measures across ecosystems (Figure 44) (Roe et al. 2021). Appropriately implemented restoration can complement, but not replace, efforts to protect the world's remaining forests, peatlands, and mangroves.[65] Not only is recovering these ecosystems often more costly than safeguarding them, but it may also take decades (if not longer) for these ecosystems to regain species diversity, ecosystem structure, and ecological functions, all of which may impact carbon cycling and GHG fluxes within these ecosystems (Sasmito et al. 2019; Poorter et al. 2021; Kreyling et al. 2021; Su et al. 2021; Cook-Patton et al. 2021; Loisel and Gallego-Sala 2022). Reforestation, as well as peatland and mangrove restoration, then, cannot cancel out the impacts of losing these ecosystems—they do not offer a one-to-one trade.

FORESTS AND LAND INDICATOR 4:
Reforestation (total Mha)

- **Targets:** Reforestation occurs across a total of 300 million hectares (Mha) between 2020 and 2050, reaching 100 Mha by 2030 and 150 Mha by 2035.[66]

All modeled pathways limiting global temperature rise to 1.5°C with no or limited overshoot rely on carbon removal, and reforestation represents a relatively cost-effective, readily available approach that, when

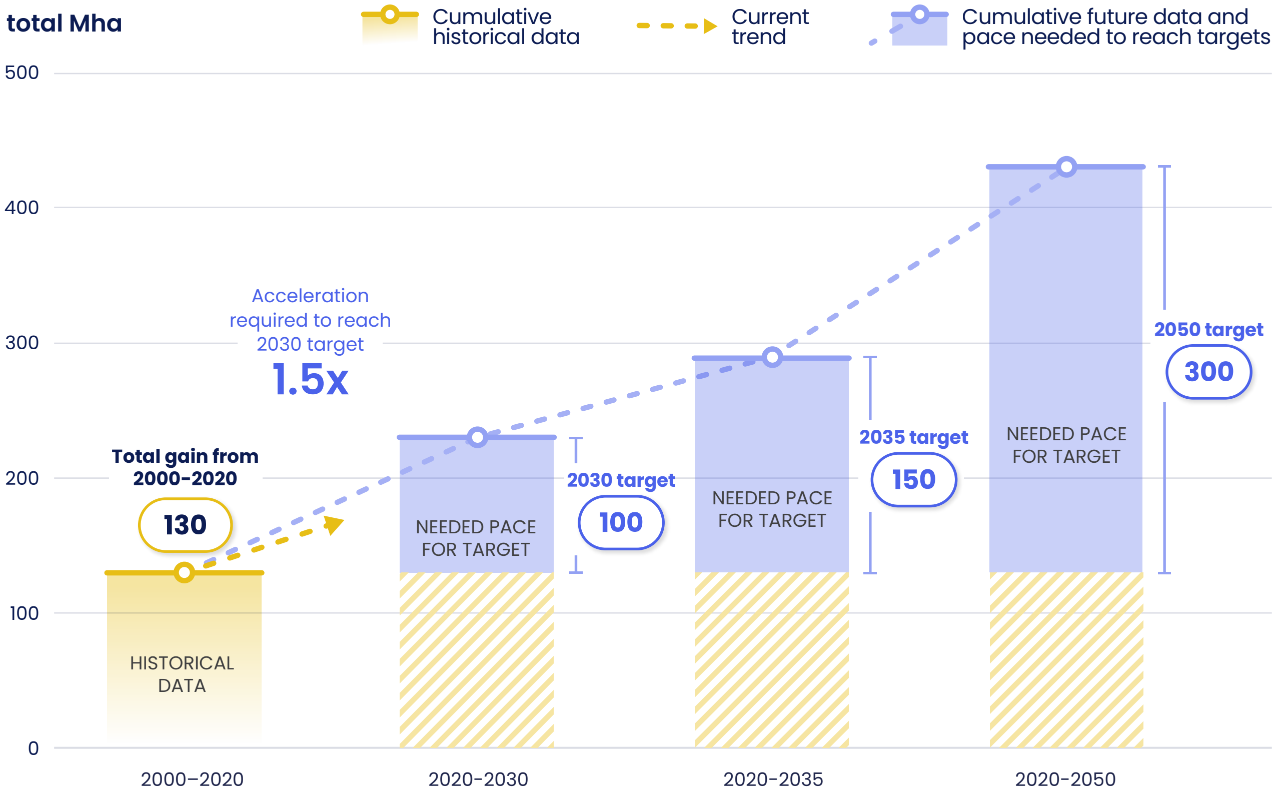
implemented appropriately (i.e., by focusing on recovering forests' ecological functions, rather than solely on reestablishing trees), can generate additional benefits to adaptation, sustainable development, and biodiversity (Figure 44) (IPCC 2022b). Yet data limitations pose significant challenges to monitoring reforestation globally, with remotely sensed data on the gross area of tree cover gain offering a best available proxy.[67] However, these data may include tree cover gains that, although potentially beneficial to climate mitigation, do not meet common definitions of reforestation and would not constitute progress toward these 2030 and 2050 targets, such as afforestation across historically nonforested lands or regrowth after harvesting within already established plantations (WRI 2023b). Also, increases in tree cover occur gradually as these plants grow and, therefore, are more challenging to reliably estimate using satellite remote sensing methods on short timescales. Still, historical cumulative data suggest that, worldwide, a total of 130 Mha experienced tree cover gain from 2000 to 2020 (Potapov et al. 2022a). Reforesting an additional 100 Mha by 2030 (Roe et al. 2021), however, will require a 1.5-fold acceleration in the average annual rate of tree cover gain from 2000 to 2020 (6.5 Mha/yr) (Figure 48).

Although global progress made toward this near-term, 1.5°C-aligned target remains off track, some countries have reestablished tree cover at or above the pace required to fulfill their national contributions to reforesting 100 Mha globally by 2030.[68] For example, should Russia, the United States, and China—countries that collectively account for just over 15 percent of the cost-effective mitigation potential for reforestation estimated by Roe et al. (2021)—sustain their recent rates of tree cover gain within historically forested areas and outside of current tree plantations, they would, together, increase their forest cover by nearly 30 Mha by 2030 (Potapov et al. 2022a). Another 50 countries have witnessed tree cover gain rates that, if maintained over this decade, would also put them on track to fulfill their national contributions to this global reforestation target (Roe et al. 2019, 2021; Potapov et al. 2022a). These gains,

FIGURE 48 | Historical progress toward 2030, 2035, and 2050 targets for reforestation

! Right Direction, Off Track

S-Curve Unlikely



Notes: Mha = million hectares. Reforestation targets are additional to any reforestation that occurred prior to 2020, and these targets are cumulative from 2020 to 2050. Following Boehm et al. (2021) and due to data limitations, the average annual rate of change across the most recently available time period (2000–2020) was used to estimate the historical rate of change, rather than a linear trendline. Also, historical data for forests and land indicators were estimated using maps derived from remotely sensed data, and accordingly, they contain a degree of uncertainty. See Jaeger et al. (2023) for more information on methods for selecting targets, indicators (including the known limitations of each), and datasets, as well as our approach for assessing progress.

Sources: Historical data from Potapov et al. (2022a); 2030 and 2050 targets adapted from Roe et al. (2021).

however, would total just 7 Mha and, therefore, would deliver smaller climate benefits relative to Russia, the United States, and China.

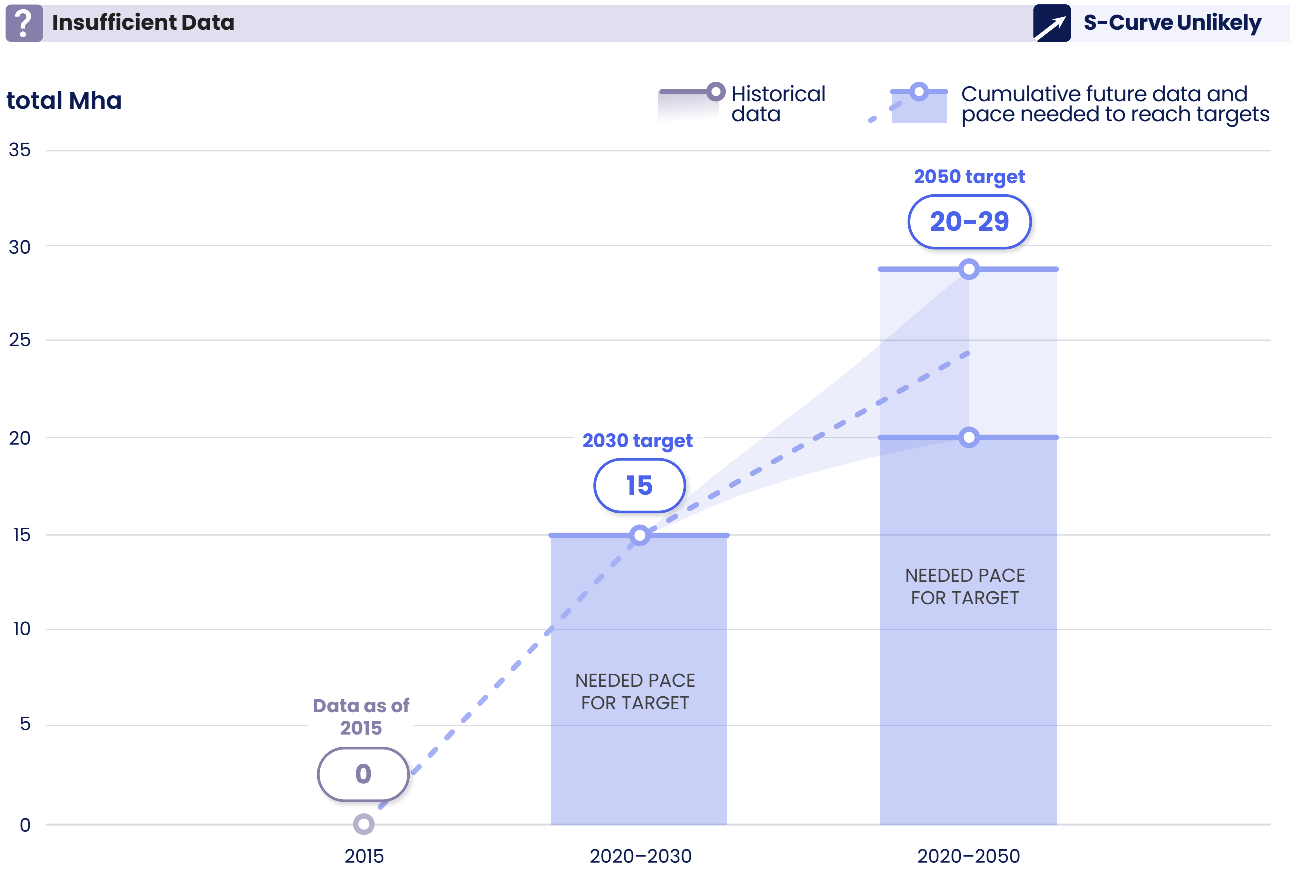
FORESTS AND LAND INDICATOR 5:

Peatland restoration (total Mha)

- **Targets:** Peatland restoration occurs across a total of 20–29 million hectares (Mha) of degraded peatlands between 2020 and 2050, reaching 15 Mha by 2030.[69]

Even if peatland degradation ended today, degraded peatlands could continue emitting roughly 1.9 $GtCO_2e$ per year for decades to centuries (Leifeld and Menichetti 2018; UNEP 2022b) because, unlike forests, peatlands store carbon primarily within their waterlogged soils rather than in aboveground vegetation. Carbon and nitrogen losses following land-use changes, then, are not immediate and continue until the soil is rewetted or all peat is lost (FAO 2020; Temmink et al. 2022). The efficacy of restoring peatlands to avoid these GHG emissions, however, will depend, in part, on what form of degradation these wetland ecosystems experienced (e.g., drainage, burning, or cutting). Rewetting peatlands drained by agriculture, for example, can significantly reduce or even halt carbon losses, as well as enable carbon sequestration (Günther et al. 2020; Mrotzek et al. 2020; Darusman et al. 2023).[70] Because drained peatlands will emit CO_2 and N_2O for decades to centuries, restoring these ecosystems' water tables should occur as quickly as possible to maximize avoided GHG emissions (Günther et al. 2020; Temmink et al. 2022). Peatland rewetting can also lower the risk of peat fires (FAO 2020), with one study estimating that, by restoring 2.5 Mha of peatlands, Indonesia could reduce fire risk by up to 30 percent (Tan et al. 2022).

FIGURE 49 | Historical progress toward 2030 and 2050 targets for peatland restoration



Notes: Mha = million hectares. Peatland restoration targets are additional to any restoration that occurred prior to 2020, and these targets are cumulative from 2020 to 2050. Peatland restoration targets were adapted from Humpenöder et al. (2020) and Roe et al. (2021), who assume that 0 Mha of peatlands globally were rewetted as of 2015. This assumption, however, does not suggest that peatland restoration is not occurring, as there is evidence of rewetting, for example, in Canada, Indonesia, and Russia (UNEP 2022b; Sirin 2022; BRGM 2023), but rather speaks to the lack of global data on peatland restoration. See Jaeger et al. (2023) for more information on methods for selecting targets, indicators (including the known limitations of each), and datasets, as well as our approach for assessing progress.

Sources: Historical data from Humpenöder et al. (2020); targets adapted from Humpenöder et al. (2020) and Roe et al. (2021), using recent estimates of degraded peatlands from UNEP (2022b).

Restoring 15 Mha of peatland—more than a quarter of all degraded peatlands worldwide—by 2030, then, can help limiting warming to 1.5°C (Humpenöder et al. 2020; Roe et al. 2021; UNEP 2022b). Although data are insufficient to assess progress toward this global target (Figure 49), available evidence suggests that current efforts to restore peatlands are occurring, but likely not at the pace and scale required (Strack et al. 2022; UNEP 2022b). From 2010 to 2013, for example, the Russian government implemented one of the largest-scale peatland rewetting projects in the Northern Hemisphere across more than 73,000 hectares near Moscow (Sirin 2022); during the early 2000s, Germany rewetted more than 20,000 hectares of peatlands in one of its northeastern states (Zerbe et al. 2013). While both initiatives represent steps forward, these restored areas account for a small fraction of the degraded peatlands within Russia and Germany (UNEP 2022b). Indonesia, in contrast, has made more recent and significant progress in restoring its degraded peatlands, with the government reporting that it restored just over 300,000 hectares in 2021 and more than 240,000 hectares in 2022 (BRGM 2021, 2023). Should Indonesia continue restoring degraded peatlands at this rate, it would restore more than 2.4 Mha by 2030 and, therefore, fulfill its national contribution to restoring 15 Mha peatland globally by the end of this decade (Humpenöder et al. 2020; Roe et al. 2021).[71]

FORESTS AND LAND INDICATOR 6:
Mangrove restoration (total ha)

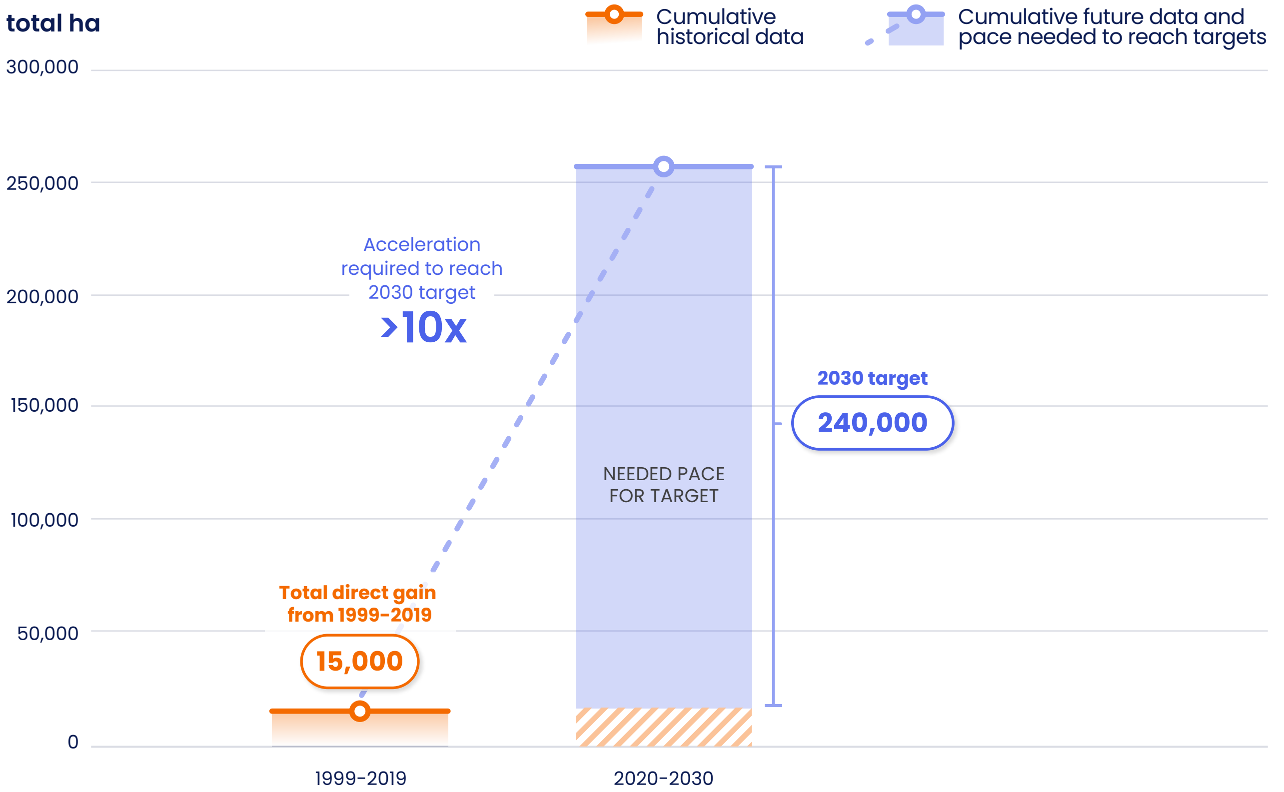
- **Target:** Mangrove restoration occurs across a total of 240,000 hectares by 2030.[72]

Restoring mangrove forests not only enhances their ability to sequester and store carbon but may also reduce GHG emissions that would have otherwise continued for decades after certain disturbances, such as the loss of soil organic carbon following drainage for aquaculture ponds (Temmink et al. 2022). Monitoring mangrove restoration, however, remains challenging. As with forests, mangroves grow gradually, and therefore restoration may be more challenging to monitor on shorter timescales, as gain may not be detected until mangrove trees reach a certain level of maturity. Moreover, the establishment of mangrove trees does not always indicate restoration of the ecological functions of these ecosystems, and in some cases, this addition of mangroves can lead to negative consequences (e.g., the loss of other coastal ecosystems) or short-lived gains if tree-planting is not implemented appropriately (Lee et al. 2019). Additionally, these coastal wetlands are naturally dynamic ecosystems, with changes also occurring due to large-scale processes that can be influenced indirectly by human activities in adjacent watersheds, such as increased sedimentation, or exacerbated by climate change impacts, such as increasing temperatures and sea level rise (Murray et al. 2022; Bunting et al. 2022; Spalding and Leal 2021).

Still, available global estimates indicate that the world gained approximately 180,000 hectares of mangrove forests from 1999 to 2019 (Murray et al. 2022).[73] A small percentage—8 percent or 15,000 hectares—of this gross gain area can be attributed to direct human interventions, such as mangrove planting or restoration activities, and all occurred in Asia and Africa (Murray et al. 2022). The vast majority of increases are instead due to indirect drivers, such as the colonization of new sediments or inland migration (Murray et al. 2022). Although mangrove gain due to direct human interventions does not indicate whether establishment of these mangroves restored the ecological function of these ecosystems, it does provide the best available proxy for mangrove restoration. These data indicate that global efforts to restore 240,000 hectares of mangrove forests by 2030 remain well off track and will require greater than a 10-fold increase in the average annual rate of direct mangrove gains (750 ha/yr from 1999 to 2019) (Figure 50).

FIGURE 50 | Historical progress toward 2030 target for mangrove restoration

☒ **Right Direction, Well Off Track** **S-Curve Unlikely**



Notes: ha = hectares. Mangrove restoration targets are additional to any restoration that occurred prior to 2020. Murray et al. (2022) estimated that a gross area of 180,000 ha (95 percent confidence interval of 0.09 to 0.30 Mha) of mangrove gain occurred from 1999 to 2019, only 8 percent of which has been attributed to direct human activities, such as mangrove planting and restoration. We estimated the most recent data point for mangrove restoration by taking 8 percent of the total gross mangrove area gained from 1999 to 2019 (15,000 ha). Following Boehm et al. (2021) and due to data limitations, the average annual rate of change across the most recently available time period (1999–2019) was used to estimate the historical rate of change, rather than a linear trendline. Also, historical data for forests and land indicators were estimated using maps derived from remotely sensed data and accordingly contain a degree of uncertainty. See Jaeger et al. (2023) for more information on methods for selecting targets, indicators (including the known limitations of each), and datasets, as well as our approach for assessing progress.

Sources: Historical data from Murray et al. (2022); 2030 target from Roe et al. (2021). Note that this target is conservative as it excludes mangrove forests lost before 1996, and previous studies suggest that mangrove losses in the 1980s and 1990s were significant (Friess et al. 2019), so much so that, by one estimate, the world may have lost as much as 35 percent of mangrove forests globally during these two decades (Valiela et al. 2001). This target, therefore, likely represents the area of mangroves that, at a minimum, needs to be restored to achieve climate mitigation goals. Those designed to build resilience would likely call for more ambitious mangrove restoration (Leal and Spalding 2022), such as the nearly 410,000 ha target set under the Mangrove Breakthrough (Global Mangrove Alliance and High-Level Champions 2023).

Sustainably manage forests and grasslands

Improving ecosystem management can also help reduce GHG emissions and enhance carbon sequestration, though management practices that optimize these mitigation benefits will vary by ecosystem and location (IPCC 2019, 2022b). For managed natural or planted forests, such practices generally include implementing reduced-impact logging (e.g., narrower roads to haul timber and felling strategies that minimize waste and avoid damage to nearby trees), extending harvest rotations to increase the age at which trees are felled, and setting aside areas protected from logging to help conserve biodiversity (Ellis et al. 2019; Austin et al. 2020; Griscom et al. 2020). Countries in temperate and boreal regions, where forestry activities drive the majority of tree cover losses (Curtis et al. 2018), can make a particularly important contribution to mitigation by improving forest management (Roe et al. 2021). In grasslands, these practices may focus on improving fire management, for example, by prescribing early dry season burns that can help minimize more extensive and severe fires later in the dry season (Lipsett-Moore et al. 2018; Griscom et al. 2020).

Collectively, such management practices account for just under 15 percent of the cost-effective mitigation potential associated with these land-based measures across ecosystems (Figure 44) (Roe et al. 2021). And while their global contribution to mitigation is small relative to protecting and restoring high-carbon ecosystems, such activities may prove less challenging to implement, as they often entail fewer changes in land use or in existing operational systems (Ellis et al. 2019; Cook-Patton et al. 2021). But despite recent advances in mapping the spatial distribution of forest management globally (Lesiv et al. 2022), detailed information on forest management practices at a global scale is not available. Similarly, no such data exists for grasslands, though global mapping and monitoring efforts are underway. Due to these data limitations, this assessment of global progress excludes targets and indicators for improved management of forests and grasslands from Roe et al. (2021).[74]

Recent developments across forests and land

While global progress made in accelerating land-based mitigation measures across forests, peatlands, and mangroves continues to fall woefully short of the changes required to help limit warming to 1.5°C, multilateral commitments to conserve these ecosystems abound. At COP26, for example, more than 140 nations signed the Glasgow Leaders' Declaration on Forests and Land Use, agreeing to halt and reverse forest loss and land degradation within the next decade (Prime Minister's Office 2021a), and in December 2022, nearly 190 Parties to the Convention on Biological Diversity adopted the Kunming-Montreal Global Biodiversity Framework, which commits signatories both to protecting at least 30 percent of the planet and to restoring another 30 percent of degraded ecosystems by 2030 (CBD 2022a). Though these new pledges reflect sustained political focus on protecting, restoring, and sustainably managing ecosystems, they do not guarantee action. Previous efforts to follow through on similar commitments have often fallen short, with governments, companies, and financial institutions collectively missing interim goals under the Bonn Challenge and the New York Declaration on Forests (IUCN 2020; NYDF Assessment Partners 2019, 2022a).

Achieving these multilateral commitments will require all countries to strengthen their conservation policies. To avoid additional losses, countries can consider, for example, placing moratoria on conversion, establishing and expanding protected areas,[75] financially incentivizing conservation (e.g., through payment-for-ecosystem-services schemes), encouraging community forest management, and legally recognizing Indigenous Peoples' land rights (Box 15), among other measures (Chaturvedi et al. 2019; NYDF Assessment Partners 2021; Wolf et al. 2021; IPCC 2022b). Similarly, restoration efforts can benefit from a range of supportive policies, from increasing public finance for these projects (e.g., by integrating restoration costs into

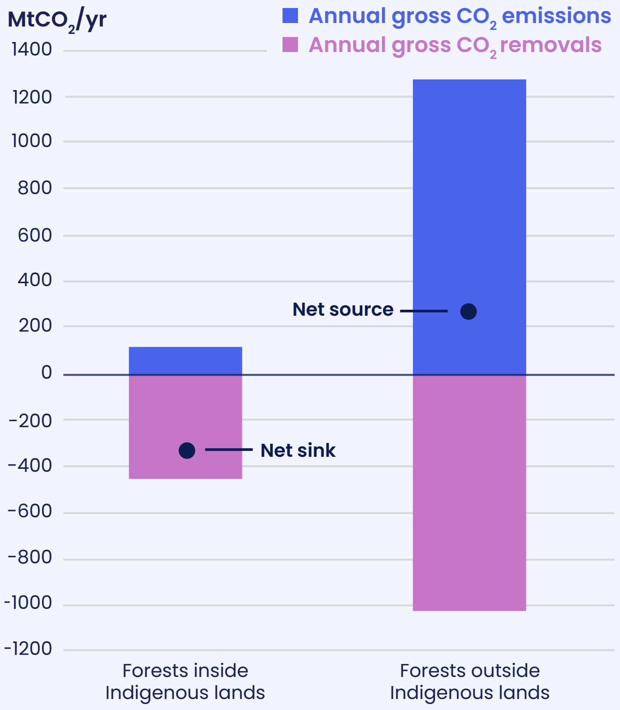
BOX 15 | Securing Indigenous Peoples and local communities' land rights underpins effective land-based mitigation

Strengthening Indigenous Peoples' tenure security offers one highly effective, relatively low-cost strategy to protect the world's remaining intact forests (Stevens et al. 2014; Ding et al. 2016), at least 36 percent of which stretch across these communities' territories (Fa et al. 2020). Several studies find that, in the tropics, deforestation across Indigenous lands is significantly lower than in nearby forests, and, in some cases, comparable to or less than losses within strictly protected areas (Nolte et al. 2013; Schleicher et al. 2017; Walker et al. 2020; Sze et al. 2022). In the Amazon basin, for example, forests managed by Indigenous Peoples removed a net 340 $MtCO_2$ per year from 2001 to 2021, while forests outside Indigenous lands were collectively a net carbon source due to substantial losses in forest cover (Veit et al. 2023) (Figure B15.1). Yet an analysis of legal frameworks in more than 70 countries covering 85 percent of Earth's land finds that, despite holding and using at least half of the world's land, Indigenous Peoples and local communities legally own just 11 percent of this land. While the total area of land legally designated for and owned by these groups increased by just over 100 Mha from 2015 to 2020, nearly 1,400 Mha—an area roughly the size of Antarctica—has not yet been recognized under national laws and regulations (RRI 2023).

Clarifying, strengthening, and upholding land rights also plays an essential role in enabling restoration. Communities need assurances that they will accrue the benefits of reestablishing trees, rewetting peatlands, or restoring mangroves. Without rights to restored lands, they may have little incentive to devote their time, labor, and resources to such projects (Gregersen et al. 2011; Hanson et al. 2015; Barrow et al. 2016; Chazdon et al. 2017; Djenontin et al. 2018; Evans 2018; Legesse et al. 2018; Lovelock and Brown 2019; Wainaina et al. 2021; IPCC 2022b). Yet tenure insecurity remains stubbornly high. Nearly 1 billion people believe they could lose part of their land or the right to use it

BOX 15 | Securing Indigenous Peoples and local communities’ land rights underpins effective land-based mitigation

FIGURE B15.1 | Annual average CO_2 flux inside and outside Indigenous lands across nine Amazonian countries from 2001 to 2021



Note: CO_2 = carbon dioxide; $MtCO_2$/yr = million tonnes of carbon dioxide per year.

Sources: Veit et al. (2023).

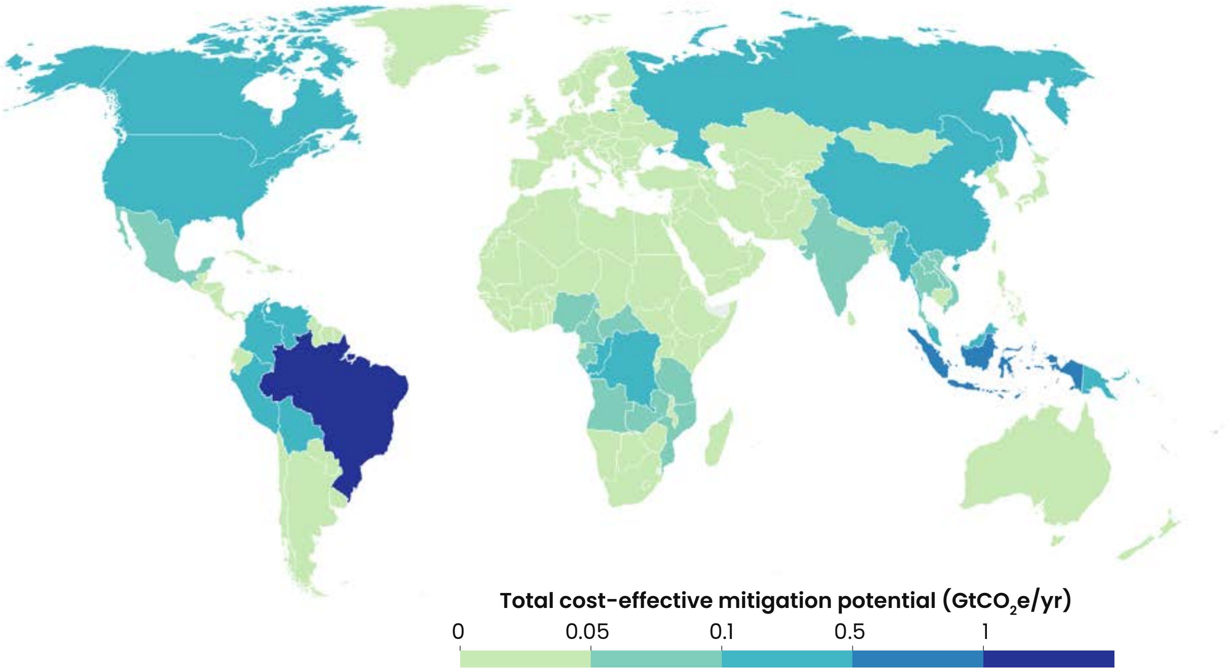
within five years (Feyertag et al. 2020), with perceived tenure insecurity above the global average in countries accounting for just over half of the cost-effective mitigation potential for restoration (Roe et al. 2021; Feyertag et al. 2020).

Meaningfully engaging Indigenous Peoples and local communities as full partners in the design, implementation, and monitoring of restoration also underpins successful projects (Höhl et al. 2020). Done well, inclusive, participatory decision-making processes enable communities living within or nearby high-carbon ecosystems to determine restoration projects’ goals, ensuring that they are appropriately tailored to local contexts; avoid exacerbating inequalities (e.g., by providing alternative livelihoods where needed); and deliver important benefits to communities (e.g., improving health outcomes or protecting culturally significant sites). These processes, in turn, can boost local support for restoration and willingness to care for ecosystems after projects end (Hanson et al. 2015; Lazos-Chavero et al. 2016; Wylie et al. 2016; Lovelock and Brown 2019; Di Sacco et al. 2021; Indrajaya et al. 2022; Pham et al. 2022). In the late 1970s, for example, the Nepalese government began devolving forest management to local communities and, in 1993, passed legislation that legally recognized community forest user groups as independent, self-governing institutions responsible for protecting and managing national forestlands. In doing so, the government granted these groups rights (i.e., access, use, exclusion, and management) to these lands, enabling local communities not only to make decisions about these forests but also to benefit from them. These community forest user groups now manage over 1.2 Mha of forested lands across Nepal (Buckingham and Ellersick 2015); in some areas, community forestry programs restored forests at an average rate of 2 percent per year from 1990 to 2010 (Niraula et al. 2013).

Indigenous and local communities are not monoliths, however, and decision-making processes should account for existing inequities between and within them. Women, for instance, often encounter obstacles to influencing land governance that range from gendered divisions of labor that assign much of the unpaid, caregiving responsibilities to them, thereby limiting the time they can devote to decision-making processes, to cultural norms that either exclude women from these forums entirely or limit their active participation (Salcedo-La Viña and Giovarelli 2021). Similarly, in Nepal, social norms across some community forest user groups favored local elites in decision-making processes and excluded those from low-income households or historically marginalized castes, effectively limiting their ability to influence, as well as benefit from, forest restoration (Buckingham and Ellersick 2015).

Notes: Mha = million hectares; $MtCO_2$ = million tonnes of carbon dioxide.

FIGURE 51 | Global distribution of cost-effective mitigation potential for forests, peatlands, mangroves, and grasslands by country



Notes: $GtCO_2e/yr$ = gigatonnes of carbon dioxide equivalent per year. Following (Roe et al. 2021), cost-effective mitigation potential includes reductions in GHG emissions and enhanced carbon sequestration available at a carbon price of up to $100/$tCO_2e$.

Source: Roe et al. (2021).

the budgets of well-funded ministries or issuing green or blue bonds) and de-risking private sector investments in restoration (e.g., first-loss capital structures) to securing land tenure and implementing complementary, land-sparing strategies (e.g., those that sustainably boost agricultural yields to help relieve competing pressures on ecosystems and free farmland for restoration) (Hanson et al. 2015; Ding et al. 2017; Chaturvedi et al. 2019; Löfqvist and Ghazoul 2019; IPCC 2022b). Recent efforts to adopt and implement these policies, however, remain uneven. This is especially true across Brazil, the Democratic Republic of the Congo, and Indonesia—three countries that, together, can deliver nearly 40 percent of cost-effective mitigation potential associated with land-based mitigation measures across ecosystems (Figure 51) (Roe et al. 2021).

Following devastating fires in 2015, Indonesia has adopted several policies to conserve its high-carbon ecosystems. These efforts included strengthening regulations to limit peatland drainage across commercial plantations, issuing a moratorium on new palm oil concessions (though this expired in September 2021), and making permanent another nationwide moratorium on new concessions in primary forests and peatlands (Budiman et al. 2021; NYDF Assessment Partners 2021; WRI 2023d; Munthe and Ungku 2021). The government also established an agency dedicated to restoring peatlands and mangroves, as well as passed social reforms to alleviate poverty and encourage sustainable land management (Budiman et al. 2021; Mursyid et al. 2021; WRI 2023d). Together, these actions have contributed to significant reductions in primary forest loss, as well as the restoration of over 33,000 hectares of mangroves in 2021 and more than 240,000 hectares of peatlands in 2022 (BRGM 2022, 2023; Weisse et al. 2023). Following this success in reducing deforestation, Norway and Indonesia announced a REDD+ deal ahead of COP27—a breakthrough after Indonesia ended their initial REDD+ agreement in 2021, citing a “lack of concrete progress”

in receiving payments for results achieved in 2016 and 2017 (NYDF Assessment Partners 2021). Under this new deal, Norway agreed to pay $56 million for verified GHG emissions reductions from 2016 to 2017, as well as issue subsequent payments under Indonesia's existing measurement, reporting, and verification protocol (Jong 2022). In 2022, Indonesia also received its first REDD+ payment of roughly $21 million from the World Bank's Forest Carbon Partnership facility for reducing deforestation, forest degradation, and related GHG emissions in the East Kalimantan province (World Bank 2022b). Sustaining these successes over the coming decades will prove critical to delivering the land-based mitigation needed to help limit warming to 1.5°C.

In Brazil, the election of President Luiz Inácio Lula da Silva signals a dramatic shift in efforts to protect the Amazon, which experienced a 15-year high in clear-cut deforestation under the previous administration (Roy 2022). Celebrated for a political track record that contributed to a 70 percent decline in deforestation between 2005 and 2013 (Nepstad et al. 2014), President Lula pledged to halt illegal deforestation, land-grabbing and other environmental crimes across the Amazon, as well as protect the rights of Indigenous Peoples and local communities (Fundação Perseu Abramo 2022). Yet he faces an uphill battle. Not only did former president Jair Bolsonaro effectively weaken ecological protections, defund environmental agencies and law enforcement, and support legislation to dismantle Indigenous Peoples' rights and legalize land-grabbing (Roy 2022), but also his right-wing political allies currently control many of the state governments in Amazonia, as well as a significant number of seats in both chambers of Brazil's Congress (Maisonnave and Jeantet 2023; Boadle 2022). Still, Lula has taken steps forward to undo this environmental backsliding by appointing well-respected environmentalists and Indigenous People to leadership roles, creating a Ministry of Indigenous Peoples, signing a decree to rejuvenate the Amazon Fund, revoking a law that allowed mining in protected areas and on Indigenous Peoples' lands, and launching anti-deforestation raids (Maisonnave and Jeantet 2023; Spring 2023). He also recently unveiled a new phase of the "Action Plan for the Prevention and Control of Deforestation in the Amazon," which sets out a four-year roadmap for halting illegal deforestation by 2030, and announced that his government would update Brazil's NDC in line with previous pledges to reduce GHG emissions 43 percent by 2030 (Associated Press 2023). Together, these measures represent promising signals of change—already, preliminary satellite data from Brazil's national space agency indicate that deforestation fell by over 30 percent during President Lula's first six months in office (Maisonnave 2023).

But in the Democratic Republic of the Congo (DRC), the government's recent efforts to conserve high-carbon ecosystems have been mixed. In July 2022, just months before President Félix Antoine Tshisekedi signed into law a historic bill recognizing Indigenous Peoples' customary forest and land rights (Gauthier 2022; RRI and DGPA 2022), the DRC placed oil and gas blocks across the country's humid tropical primary forests and peatlands up for auction (Dummett 2022). If sold, these permits would allow drilling in Virunga National Park, one of Africa's most biodiverse landscapes and a sanctuary for endangered mountain gorillas (Nyemba and Ross 2022). They would also enable fossil fuel extraction across at least 1 Mha of peatlands (Dummett 2022) within the central Congo basin, a region that, in total, contains an estimated 29 GtC (Crezee et al. 2022). In the face of pressure from the international community, the minister of hydrocarbons recently delayed the deadline for companies to submit applications for the oil blocks to between April and October 2023 (Lo 2023), but they remain for sale.

Although just a handful of countries, including Indonesia, Brazil, and the Democratic Republic of the Congo, can deliver the majority of the world's cost-effective, land-based mitigation potential (Roe et al. 2021), much of the demand to produce commodities that drive ecosystem loss, spur degradation, and impede restoration originates in the world's wealthiest countries. Between 29 and 39 percent of GHG emissions from tropical deforestation, for example, were embodied in internationally traded commodities from 2010 to 2014 (Pendrill et al. 2019b), with developed countries and emerging economies, specifically, importing an increasingly large share of deforestation embodied in commodities (Pendrill 2019a). Some governments are beginning to regulate these imported commodities. The European Union, for example, recently adopted a landmark regulation that mandates all companies to conduct due diligence on palm oil, cattle, soy, coffee, cocoa, timber, rubber, charcoal, and wood, as well as on goods derived from these commodities (e.g., chocolate, leather, or furniture), that they sell within or export from the European Union to ensure that these products are produced without deforesting or degrading forests after December 31, 2020. This law encompasses both legal and illegal deforestation, as well as forest degradation, and will require companies to trace these commodities back to where they were first produced (European Commission 2022e; European Parliament 2023e).

A handful of other countries have also passed or are considering similar regulations. The United Kingdom, for example, recently adopted the Environment Act 2021, which includes a provision requiring companies that sell forest-risk commodities to ensure that their products are free from illegal deforestation by conducting due diligence. However, enforcement cannot begin until the British parliament passes additional legislation that clarifies the scope of "forest-risk commodities (U.K. Government 2021; DEFRA 2022)." In 2021, a bipartisan group of policymakers introduced a similar piece of legislation in the United States, the Fostering Overseas Rule of Law and Environmentally Sound Trade (FOREST) Act, though it needs to be reintroduced in this session of Congress (Schatz 2021b). Even if fully adopted and implemented, both pieces of legislation would apply to illegal deforestation only (Neslen 2023; U.K. Government 2021; Schatz 2021a)—a decision that not only makes these proposed regulations less comprehensive than the European Union's directive but also increases the difficulty of enforcement, as definitions on the legality of deforestation vary significantly by country.

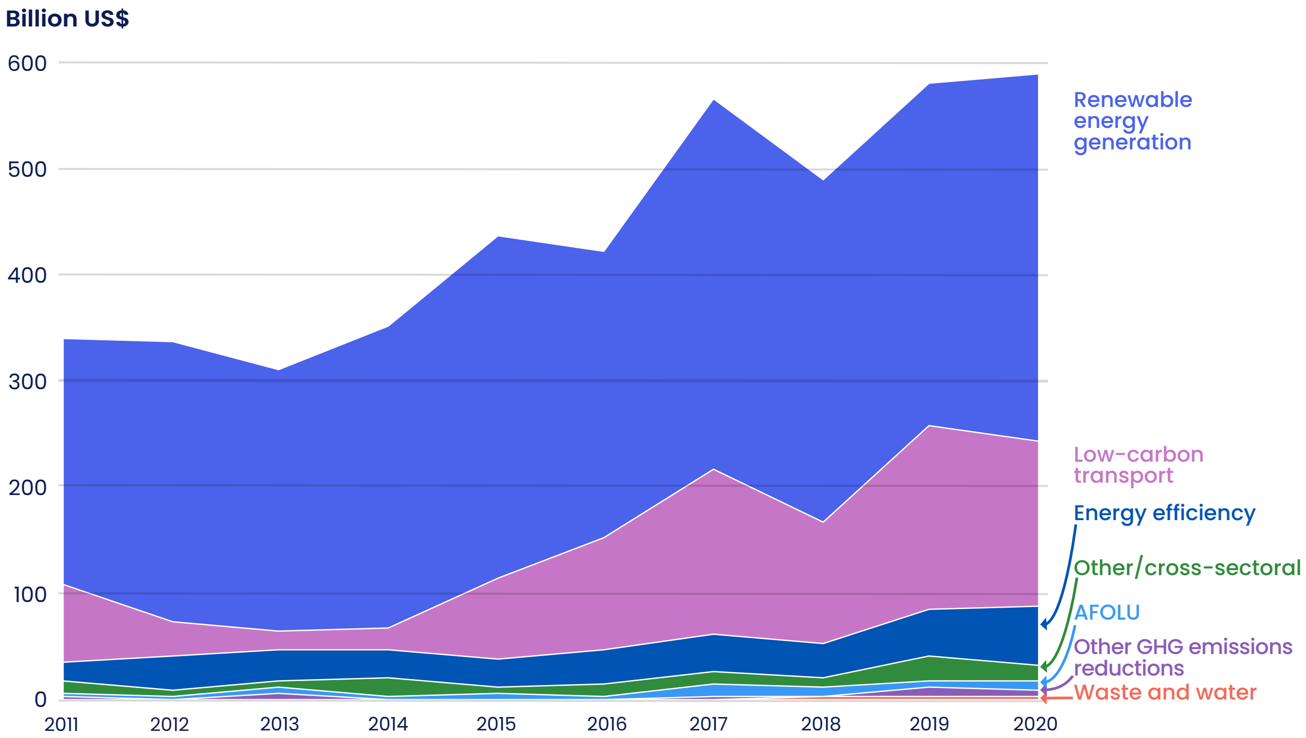
Moreover, evidence assessing the impacts of these relatively new deforestation policies remains limited, with one recent analysis finding that restrictions on palm oil imports, alone, may not significantly reduce deforestation due to leakage (Busch et al. 2022). The efficacy of these demand-side regulations, then, will likely depend on the extent to which they are adopted across consumer country governments, particularly in China, the United States, and India—countries that, alongside the European Union and the United Kingdom, collectively accounted for over 70 percent of deforestation emissions embodied in international trade flows on average between 2010 and 2014 (Pendrill et al. 2019b). Complementary policies focused on reducing domestic demand for these commodities may also be needed, as consumption of beef, soy, and palm oil remains high in a number of producer countries (Pendrill et al. 2019a).

In addition to reducing demand for commodities whose production drives ecosystem loss and degradation, increasing dedicated financial flows to land-based mitigation is vital to accelerating the transformational changes required for limiting warming to 1.5°C. But despite AFOLU's significant potential to help limit warming to 1.5°C, as well as the low costs and clear benefits of action, mitigation efforts across this sector attracted disproportionately fewer investments than nearly all other sectors over the last decade (Figure 52). Public and private funds for land-based measures continue to lag far behind estimated needs, which the IPCC (2022b) estimates will reach nearly $100 billion to $300 billion per year by 2030 and over $400 billion per year by 2050. But while total tracked climate mitigation finance earmarked for AFOLU roughly doubled over this decade, it was just under $10 billion in 2020 (Buchner et al. 2021). Limiting global warming to well below 2°C will require these recent mitigation investments to increase much faster this decade—by a factor of 10 to 31 by 2030 (see Finance Indicators 1–3) (IPCC 2022b).

Worse still, efforts to align broader financial flows across AFOLU with 1.5°C pathways remain inadequate (NYDF Assessment Partners 2022b). For example, just 6 percent of agricultural subsidies across Organisation for Economic Co-operation and Development (OECD) countries and 11 major developing nations, valued at roughly $600 billion per year from 2019 to 2021, support climate or conservation objectives (Searchinger et al. 2020; OECD 2022c), and many still incentivize environmentally harmful actions (e.g., the European Union's payments to drainage-based peatland agriculture) (Tanneberger et al. 2021). Additionally, the world's leading financial institutions channeled some $6.1 trillion to 350 companies with the highest exposure to tropical deforestation risks within their supply chains in 2022—up from $5.5 trillion in 2021 (Forest 500 2022, 2023).

At COP26, many governments, companies, and financial institutions vowed to change course. More than 30 financial institutions managing assets valued at over $8.7 trillion committed to eliminating agricultural commodity-driven deforestation risks from their lending and investment portfolios by 2025 (Race to Zero 2021). Governments also pledged $12 billion in support of the

FIGURE 52 | Total tracked climate finance for mitigation by solution



Notes: AFOLU = agriculture, forestry, and other land uses; GHG = greenhouse gas.
Source: Naran et al. (2022).

Glasgow Leaders' Declaration on Forests and Land Use, while private sector leaders promised to deliver another $7.2 billion (Prime Minister's Office 2021b). Referencing this declaration, governments and philanthropies committed $1.7 billion to help secure the forest tenure rights of Indigenous Peoples and local communities ("COP26 IPLC Forest Tenure Joint Donor Statement" 2021).

One year later, at COP27 in Sharm el-Sheikh, 26 countries and the European Union launched the Forests and Climate Leaders' Partnership in support of the Glasgow Leaders' Declaration of Forests. They reported that governments had disbursed nearly $2.7 billion of the $12 billion pledged at COP26, as well as announced commitments to channel another $4.5 billion in public and private funding toward halting and reversing forest loss (Cabinet Office and the Rt Hon Rishi Sunak MP 2022). As of November 2022, donors had also contributed just over $320 million toward the $1.7 billion pledged in support of Indigenous Peoples and local communities, though just 7 percent of this funding went directly to institutions headed by Indigenous Peoples and local communities (Forest Tenure Funders Group 2022). And just weeks after COP27, nearly 190 countries agreed to mobilize at least $200 billion per year by 2030 to safeguard biodiversity, including within forests, peatlands, and mangroves, under the landmark Kunming-Montreal Global Biodiversity Framework (CBD 2022b). Although promising, particularly the financial commitment made under the Convention on Biological Diversity, this recent wave of pledges must materialize quickly and additional pledges will be needed after this decade to deliver the more than $400 billion needed per year by 2050 (IPCC 2022b).

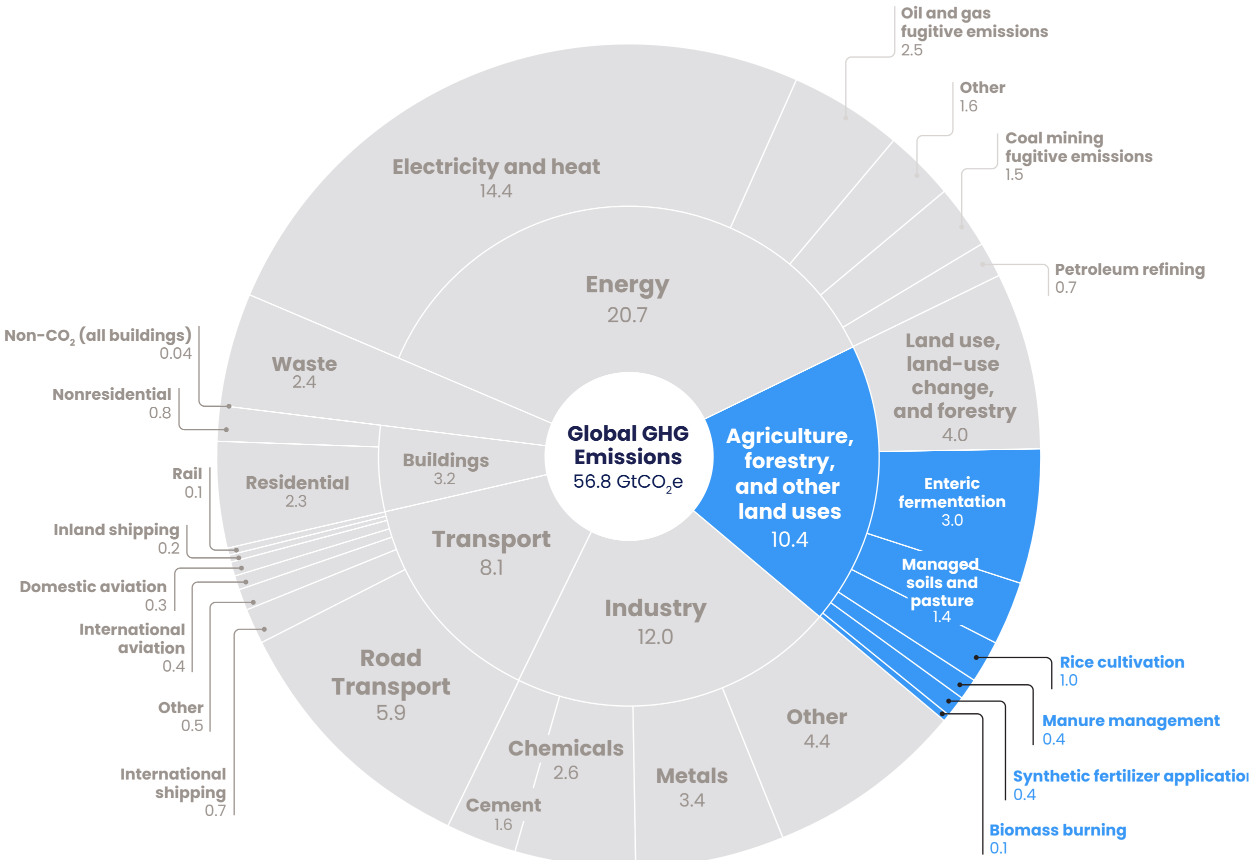
SECTION 7

Food and Agriculture

As the world's population climbs from roughly 8 billion in 2023 to nearly 10 billion by 2050 (UNDESA 2022), feeding more people, more nutritiously, while advancing socioeconomic development and reducing GHG emissions from agriculture and food systems will be a major challenge. Worldwide, more than one-quarter of employed people worked in agriculture in 2019 (World Bank 2021a). Because so many people's livelihoods depend on agriculture, and because the sector is particularly vulnerable to climate change, achieving a just transition to lower-emitting and more resilient food systems will be critical (Viglione 2021). Global food demand is on track to rise by 45 percent or more between 2017 and 2050 based on estimates of population and income growth, along with changing dietary patterns (Falcon et al. 2022; Searchinger et al. 2021). Yet, as of 2022, between 691 and 783 million people were affected by hunger, an increase of more than 100 million people since the onset of COVID-19 (FAO 2023). Furthermore, in 2022, 3.1 billion people could not afford a healthy diet, 112 million more people than in 2019 (FAO 2023). While these inequalities in people's access to food persist, growth in per capita meat consumption, as well as the expansion of bioenergy production, add to agriculture's already-growing land demands and GHG emissions.

Taken together, recent research shows that achieving global food and nutrition security in the coming decades, while limiting warming to 1.5°C, will only be possible with significant changes in food production and consumption (Clark et al. 2020). Shifting demand for food and agricultural products, sustainably increasing productivity, and changing on-farm practices and technologies, combined, are necessary to reduce the sector's global emissions and land footprint. If implemented appropriately, these changes should also have important positive effects on biodiversity, soil health, water quantity and quality, air quality, public health, equity, and agricultural livelihoods (Willett et al. 2019; IPCC 2022b). To fully address hunger and food insecurity, changes to food production and consumption must also be paired with broader interventions to address poverty, gender disparities, and political instabilities (FAO 2023).

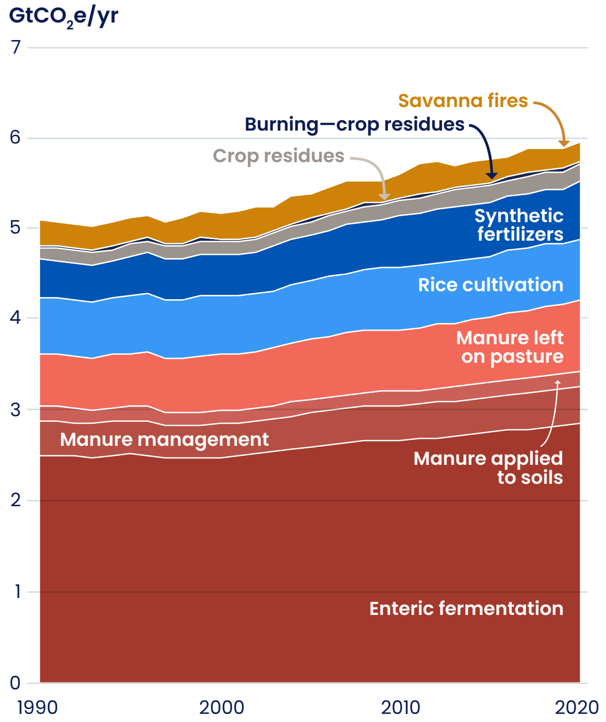
FIGURE 53 | AFOLU's contribution to global net anthropogenic GHG emissions in 2021



Notes: AFOLU = agriculture, forestry, and other land uses; CO$_2$ = carbon dioxide; GHG = greenhouse gas; GtCO$_2$e = gigatonnes of carbon dioxide equivalent.

Sources: Minx et al. (2021); European Commission and JRC (2022), using CO$_2$ emissions data for land use, land-use change, and forestry from the three bookkeeping models in the "Global Carbon Budget 2022" (Friedlingstein et al. 2022b).

FIGURE 54 | Global GHG emissions from agriculture



Notes: GHG = greenhouse gas; GtCO$_2$e/yr = gigatonnes of carbon dioxide equivalent per year. This figure only includes GHG emissions from agricultural production.

Source: FAOSTAT (2023).

GHG emissions from agricultural production, including those from cropland and pastures, contribute significantly to global GHG emissions, and in 2021 they accounted for more than half of GHG emissions from agriculture, forestry, and other land uses (AFOLU) (Figure 53) (European Commission and JRC 2022; Minx et al. 2021). These emissions have been growing at an average annual rate of 0.7 percent since 2000 (Figure 54),[76] reaching roughly 6 GtCO$_2$e in 2020 (FAOSTAT 2023). And when these production-related emissions are combined with those from land-use change, energy-related emissions across food supply chains (from the energy-related sectors in Figure 53), and methane emitted from food waste in landfills (from the waste sector in Figure 53), total food system emissions accounted for about 16 GtCO$_2$e per year—or almost 30 percent of global GHG emissions (Tubiello et al. 2022).[77]

Global assessment of progress for food and agriculture

Transforming the world's food and agriculture systems to feed a growing population sustainably and nutritiously, while limiting global warming to 1.5°C and ending ecosystem losses and degradation, will require several interconnected shifts. First, the world will need to produce more food and feed on existing agricultural lands, while reducing agricultural production emissions and other environmental impacts. This includes both lowering the emissions intensity of agricultural production and sustainably boosting crop yields and livestock productivity—all while safeguarding soil and water resources and building resilience to climate change. At the same time, reducing projected growth in demand for land-intensive goods, particularly by high-income consumers, is also a priority. This includes reducing food loss and waste, as well as reducing per capita ruminant meat (e.g., beef) consumption in high-consuming regions and avoiding bioenergy expansion. These shifts in food production and consumption, in turn, can help reduce the amount of land dedicated to agriculture and thereby enable the protection of the world's remaining natural ecosystems from agricultural conversion, as well as the restoration of degraded ecosystems into productive agriculture or (where improvement potential is limited) back to nature. Ecosystem protection and restoration are covered in more depth in Section 6, Forests and Land.

Major changes in practices, technologies, and policies will be needed in this sector both to adapt to climate change and to limit warming to 1.5°C. To ensure that farmers, ranchers, and farmworkers do not have to bear the brunt of these changes, they must have the chance to meaningfully participate in the design, implementation, and governance of adaptation and mitigation strategies. This is especially true of smallholders, Indigenous People, women, and other vulnerable groups. This approach is in line with the Paris Agreement, which encourages national plans on climate change to include just transition measures that prioritize decent work and quality jobs (UNFCCC 2020).

Progress in the food and agriculture sector remains challenging. Efficiency improvements in agriculture and the wider food system—while encouraging—are not yet keeping pace with continued growth in global demand for food and agricultural products. This year's snapshot

TABLE 6 | Summary of global progress toward food and agriculture targets

INDICATOR	MOST RECENT DATA POINT (YEAR)	2030 TARGET	2035 TARGET	2050 TARGET	LIKELIHOOD OF FOLLOWING AN S-CURVE	ACCELERATION FACTOR	STATUS
GHG emissions intensity of agricultural production (gCO_2e/1,000 kcal)	700 (2020)	500	450	320	↗	3x	✕
Crop yields (t/ha)	6.6 (2021)	7.8	8.2	9.6	↗	>10x	✕
Ruminant meat productivity (kg/ha)	29 (2021)	33	35	42	↗	1.2x	!
Share of food production lost (%)[a]	13 (2021)	6.5	6.5	6.5	↗	N/A; U-turn needed[b]	⮌
Food waste (kg/capita)[c]	120 (2019)	61	61	61	↗	Insufficient data	?
Ruminant meat consumption (kcal/capita/day)[d]	91 (2020)[e]	79	74	60	↗	8x	✕

Notes: gCO_2e/1,000 kcal = grams of carbon dioxide equivalent per 1,000 kilocalories; GHG = greenhouse gas; kcal/capita/day = kilocalories per capita per day; kg/capita = kilograms per capita; kg/ha = kilograms per hectare; t/ha = tonnes per hectare. See Jaeger et al. (2023) for more information on methods for selecting targets, indicators, and datasets, as well as our approach for assessing progress.

[a] Food loss occurs before food gets to market.

[b] Due to data limitations, an acceleration factor was calculated for this indicator using a linear trendline estimated with three data points across six years.

[c] Food waste occurs at the retail level and in homes and restaurants, among other locations.

[d] This diet shift applies specifically to the high-consuming regions (Americas, Europe, and Oceania). It does not apply to populations within the Americas, Europe, and Oceania that already consume less than 60 kcal/capita/day, have micronutrient deficiencies, and/or do not have access to affordable and healthy alternatives to ruminant meat.

[e] Consumption data are given in availability, which is the per capita amount of ruminant meat available at the retail level and is a proxy for consumption.

Sources: Historical data from FAOSTAT (2023) and UNEP (2021e). Targets derived from Searchinger et al. (2019, 2021); and United Nations (2015).

reflects another year of COVID-era data (from 2020 to 2021) and slower progress in the food and agriculture sector than noted in *State of Climate Action 2022*. As shown in Table 6, the acceleration factors in the categories of agricultural emissions intensity, ruminant meat consumption, and crop yields actually grew larger since Boehm et al. (2022) and remain well off track, indicating that 2030 targets are slipping further out of reach. New data on the rate of food loss between 2016 and 2021 show a trend moving in the wrong direction at the global level, although progress across different regions is mixed. Of all the global food and agriculture indicators in Table 6, only ruminant meat productivity has a slightly lower rate of change needed (i.e., acceleration factor) than in last year's report, and even this indicator remains off track for 2030. Furthermore, total global emissions from food production continue to grow, and croplands and pasture continue to expand into natural ecosystems like tropical forests (FAOSTAT 2023; Potapov et al. 2022b; Goldman et al. 2020). If these trends continue, global goals to eliminate deforestation and peatland degradation (Forests and Land Indicators 1–3), achieve hundreds of millions of hectares of ecosystem restoration (Forests and Land Indicators 4–6), and limit global warming to 1.5°C will become increasingly difficult to achieve.

Reduce GHG emissions from agricultural production

Emissions from agricultural production are primarily of methane and nitrous oxide, two potent greenhouse gases (Figures 53 and 54). Although global emissions from methane and nitrous oxide—including those from agricultural production—need to be greatly reduced to limit warming to 1.5°C, both modeled pathways from integrated assessment models and those from bot-

TABLE 7 | Projected agricultural production GHG emissions by major source in a 1.5°C-aligned pathway

EMISSIONS SOURCE	RECENT CHANGE IN ABSOLUTE EMISSIONS (2016–20) (%)	2030 ABSOLUTE EMISSIONS REDUCTION FOR 1.5°C PATHWAY, RELATIVE TO 2017 (%)	2035 ABSOLUTE EMISSIONS REDUCTION FOR 1.5°C PATHWAY, RELATIVE TO 2017 (%)	2050 ABSOLUTE EMISSIONS REDUCTION FOR 1.5°C PATHWAY, RELATIVE TO 2017 (%)
Enteric fermentation	+3	-17	-20	-29
Manure management	+2	-21	-26	-39
Manure on pasture	+5	-14	-15	-20
Soil fertilization	+5	-23	-27	-39
Rice cultivation	+1	-23	-29	-45
Total	**+3**	**-22**	**-26**	**-39**

Note: GHG = greenhouse gas.
Sources: Historical data from FAOSTAT (2023); 2030, 2035, and 2050 1.5°C pathway estimates derived from Searchinger et al. (2019).

tom-up, sectoral studies indicate that they do not fall to zero by midcentury the way carbon dioxide emissions do. Methane and nitrous oxide emissions remain positive in all pathways that limit warming below 2°C and even below 1.5°C (IPCC 2022b). This report's 1.5°C-aligned target for agricultural production emissions is a 39 percent *absolute* reduction by 2050 relative to 2017 (Table 7).[78] Because global population and food demand are projected to continue growing through at least the year 2050, the emissions *intensity* of agricultural production per calorie of food produced will need to fall even faster than this 39 percent absolute target.

There is currently much interest in the potential to mitigate climate change and reduce net agricultural emissions through soil carbon sequestration on working agricultural (crop and pasture) lands. Such practices are often called "regenerative" and include agroforestry, silvopasture, rotational grazing, cover cropping, crop diversification, and no-till or minimal tillage. These practices, in general, will be helpful to improve soil health and water infiltration, increase on-farm biodiversity, reduce soil erosion, reduce reliance on chemical inputs and their associated emissions, improve resilience, and maintain agricultural productivity in a changing climate. These practices will be especially important in resource-limited production systems, where they can sustainably improve productivity while enhancing adaptive capacity. That said, although these practices have been shown to build carbon at the field level (Minasny et al. 2017), and some researchers extrapolate such estimates over many hectares to estimate substantial potential reductions in net global agricultural emissions through soil carbon sequestration (Roe et al. 2021), others argue that the true global mitigation potential of these practices is uncertain (FOLU 2023; Henderson et al. 2015; Poulton et al. 2018). Better data will also be needed to track changes in global agricultural soil carbon stocks over time (IEA et al. 2022a).

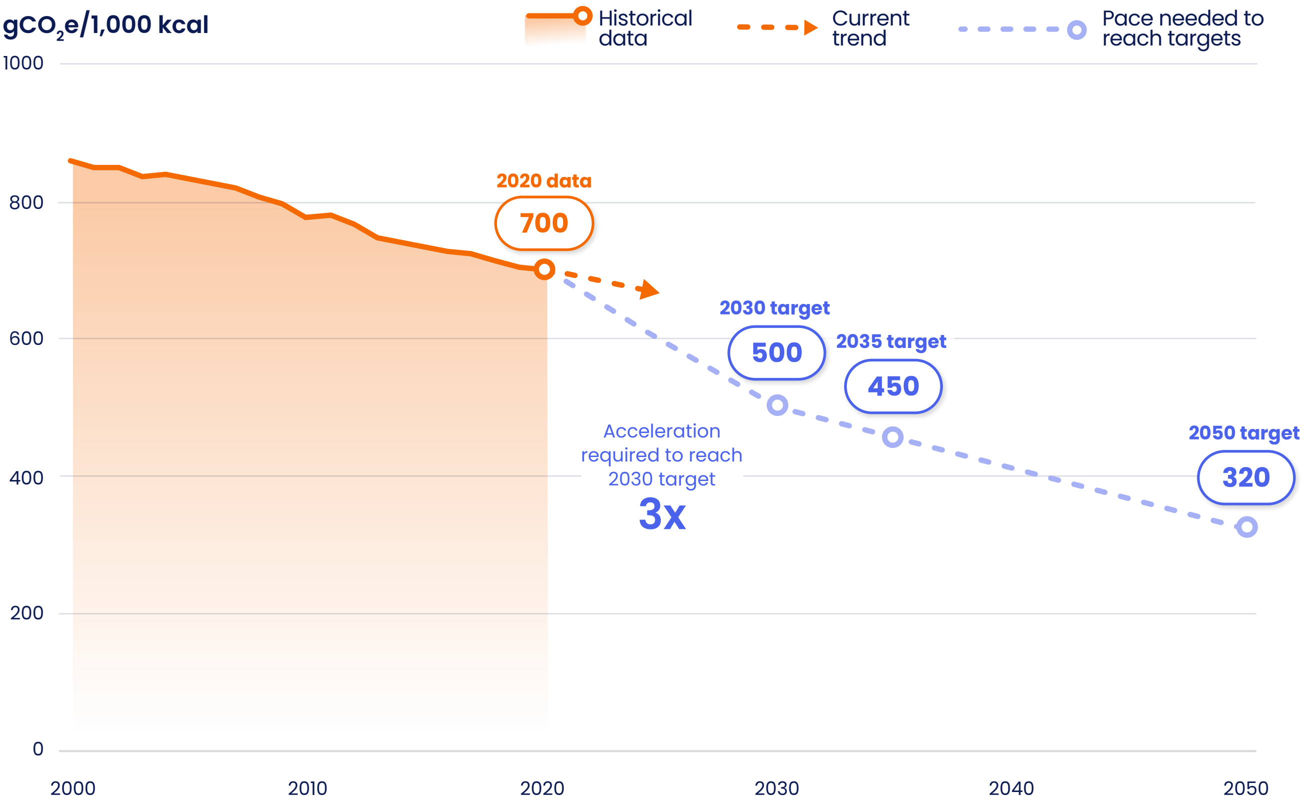
FOOD AND AGRICULTURE INDICATOR 1:
GHG emissions intensity of agricultural production (gCO_2e/1,000 kcal)

- **Targets:** Global GHG emissions intensity of agricultural production declines 31 percent by 2030, 38 percent by 2035, and 56 percent by 2050, relative to 2017.

The emissions intensity of agricultural production, as measured in grams of CO_2e per 1,000 kilocalories (kcal) in the global food supply, has been falling for decades, driven largely by steady gains in the efficiency of crop and livestock production.[79] Between 2016 and 2020, for example, GHG emissions intensity declined by 3 percent (FAOSTAT 2023) (Figure 55). That said, total absolute agricultural emissions have yet to peak globally, increasing by about 3 percent between 2016 and 2020 (FAOSTAT 2023). But to feed a growing world population while achieving necessary reductions in absolute agricultural emissions by 2030, agricultural emissions intensity would need to decline three times faster than it did between 2016 and 2020. Changes to food production practices, as well as to consumption patterns (e.g., amount of food loss and waste, share of animal-based foods in diets, and share of agricultural products used as bioenergy), will also be necessary to help achieve this required decline in emissions intensity. In particular, a "protein transition" is needed that includes both shifting

FIGURE 55 | Historical progress toward 2030, 2035, and 2050 targets for GHG emissions intensity of agricultural production

☒ **Right Direction, Well Off Track** **S-Curve Unlikely**



Note: gCO$_2$e/1,000 kcal = grams of carbon dioxide equivalent per 1,000 kilocalories; GHG = greenhouse gas. See Jaeger et al. (2023) for more information on methods for selecting targets, indicators, and datasets, as well as our approach for assessing progress.

Sources: Historical data from FAOSTAT (2023); targets derived from Searchinger et al. (2019).

toward more sustainably produced livestock products, as well as increased consumption of plant proteins and alternative proteins with lower environmental impacts; strategies relying only on production-side or consumption-side measures are likely to be insufficient (Searchinger et al. 2019; Roe et al. 2019; IPCC 2022b).

Sustainably increase crop and livestock productivity on existing agricultural land

Agricultural research has traditionally focused on enhancing productivity, and, as a result, yields of both crops and livestock products (meat and milk) per hectare have risen steadily for decades. Boosting productivity allows more food to be produced on a smaller land area, which can avoid GHG emissions from land-use change (e.g., deforestation) and/or enable carbon removal through ecosystem restoration. That said, the need to feed a growing population—while finally halting agricultural expansion into forests and allowing some agricultural areas to be restored into natural ecosystems—means that yield gains will need to accelerate in the coming decades relative to recent years (Searchinger et al. 2019).

This challenge is compounded by the fact that food production is highly vulnerable to climate change. The IPCC's Sixth Assessment Report finds that climate change is already stressing agriculture, fisheries, and aquaculture. Heat extremes, droughts, floods, and other climate-related hazards have reduced agricultural productivity, disrupting food supplies and livelihoods. Since 1961, productivity growth in African agriculture has been one-third lower than it would have been without climate change (Ortiz-Bobea et al. 2021), and crop yields in Africa remain far below the global average (FAOSTAT 2023). Risks and vulnerabilities in the sector—including loss of income or livelihoods, and rising competition over resources—are very likely to worsen in a warmer climate, and are likely to most heavily affect vulnerable populations such as women, youth, small-scale producers, farmworkers, low-income households, and Indigenous and other marginalized groups (IPCC 2022a).

Productivity increases will need to occur in a changing climate; thus, it will be necessary to rely on approaches that increase resilience, safeguard soils, protect freshwater resources, minimize pollution, and avoid a "rebound effect." This effect can occur where gains in crop or livestock productivity lead to increased profits from farming, fueling additional expansion of agriculture into natural ecosystems. To avoid this rebound effect, incentives for productivity improvements will need to be linked to natural ecosystem protection, equity, and restoration (Searchinger et al. 2019).

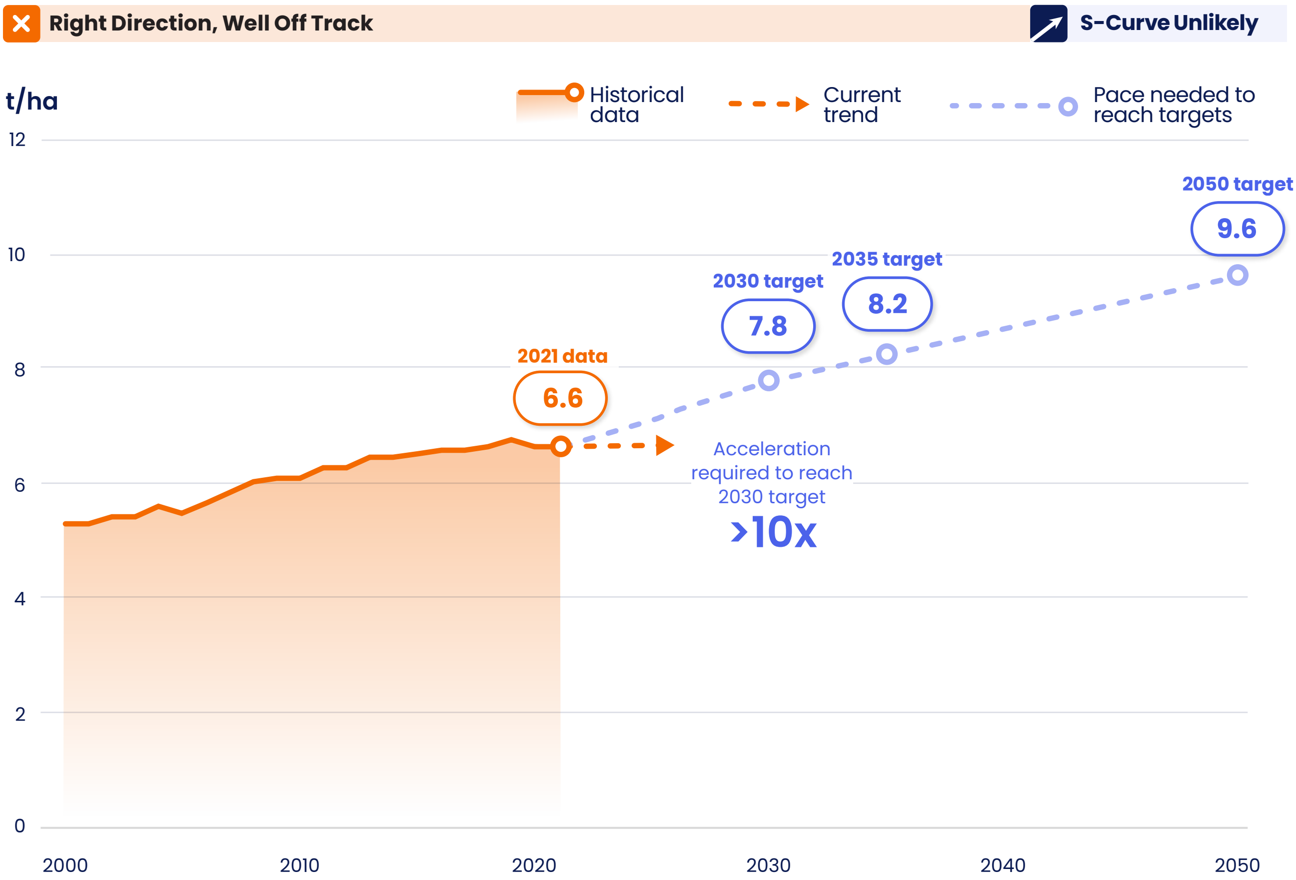
FOOD AND AGRICULTURE INDICATOR 2:
Crop yields (t/ha)

- **Targets:** Crop yields increase by 18 percent by 2030, 25 percent by 2035, and 45 percent by 2050, relative to 2017.

Global crop yields, expressed in tonnes of crops produced per hectare of cropland,[80] remained flat between 2020 and 2021 and below a historical peak in 2019. In 2021, yields were only 0.7 percent above 2017 levels (FAOSTAT 2023) (Figure 56), representing a worrying continuation of recent trends. Because of this recent slow growth, crop yield growth needs to accelerate more than 10-fold to reach the 2030 target, meaning that global progress remains well off track.

The COVID-19 pandemic exacerbated global food insecurity in 2020 and 2021. Food prices rose, supply chains were disrupted, and social protection measures were inadequate (FAO 2022b). Food production itself was hampered, as lockdowns and travel bans limited access to farm inputs, input costs rose, and farmers faced labor shortages (Sridhar et al. 2023). That said, FAOSTAT data paint a less clear-cut picture of the effects of COVID-19 on crop production. For example, despite these enormous difficulties, global cereal crop production reached a record high in 2020 and again in 2021, at 3.1 billion tonnes. In 2021, global cereal yields reached a record high of 4.15 tonnes/ha/yr, after a one-year decline between 2019 and 2020 (FAOSTAT 2023). The

FIGURE 56 | Historical progress toward 2030, 2035, and 2050 targets for crop yields



Note: t/ha = tonnes per hectare. See Jaeger et al. (2023) for more information on methods for selecting targets, indicators, and datasets, as well as our approach for assessing progress.

Sources: Historical data from FAOSTAT (2023); targets derived from Searchinger et al. (2019, 2021).

Ukraine-Russia war has also affected two major cereal and oilseed producers and exporters since 2022, and the war's impact is not yet reflected in the global FAOSTAT data. However, national-scale estimates are stark: cereal and oilseed crop production projections for Ukraine's 2022–23 growing season are 30–40 percent below the 2021–22 level (Martyshev et al. 2023).

Yields in Africa continue to stagnate at a low level as they have for decades; for example, in 2021, yields of cereal crops in Africa, which underpin food security, were only 42 percent of the world average and 30 percent of cereal yields in the Americas (FAOSTAT 2023). Improving crop yields on small farms in Africa is also a key lever for reducing poverty (IFPRI 2022). Improved seeds, soil fertility improvement, water management, extension services, access to markets and credit, and improved weather forecasting are all critically important to sustainably boosting smallholders' yields across the African continent (Jama and Pizarro 2008)—this in turn will be important for limiting agricultural expansion into natural ecosystems.

Recent satellite-based evidence of ongoing cropland expansion (Potapov et al. 2022b) suggests that yield growth has not kept pace with crop demand growth in the 21st century, as 102 Mha of land were converted to annual crops between 2003 and 2019. Most of the cropland expansion occurred in Africa (53 Mha) and South America (34 Mha) (Potapov et al. 2022b), driven by growth in both local food demand and global demand for crop commodities grown in those regions. While commodity-driven expansion—such as land-clearing for soybean production—is dominant in South America, in Africa cultivation of crops for domestic use seems to be the biggest contributor to expansion (Curtis et al. 2018).

FOOD AND AGRICULTURE INDICATOR 3:

Ruminant meat productivity (kg/ha)

- **Targets:** Ruminant meat productivity per hectare rises 27 percent by 2030, 35 percent by 2035, and 58 percent by 2050, relative to 2017.

The way that meat and milk from ruminant livestock (e.g., cattle, sheep, goats) are produced and consumed has a major bearing on the land use demands and GHG emissions of global agriculture. Ruminant livestock use more than two-thirds of agricultural land and account for about half of agricultural GHG emissions, even when excluding emissions from feed production (FAOSTAT 2023) (Figure 54). And while ruminant livestock production plays a key role in the rural economies and cultures of developing countries, provides livelihoods and high-quality protein to millions of pastoralists, and makes use of arid lands that could not otherwise produce crops, the continued global growth in meat and milk demand will increase pressures on the world's remaining natural ecosystems. Meat production is particularly resource-intensive. Therefore, sustainably increasing ruminant meat productivity, reducing GHG emissions from its production, and moderating ruminant meat consumption in high-consuming regions as part of a "protein transition" will all be essential to reduce emissions from livestock while feeding more people (Searchinger et al. 2019). These changes can also support efforts to conserve biodiversity (Semenchuk et al. 2022).

Ruminant meat productivity describes the amount of meat from ruminant livestock produced per hectare of pastureland. In 2021, ruminant meat productivity per hectare was 6 percent higher than in 2017 (Figure 57), a new historical high and a continuation of recent trends. The basic mechanisms for these productivity gains have been improvements in feed efficiency (e.g., through use of more digestible feeds); planting and fertilizing pastures with improved grasses, legumes, trees, and shrubs (Box 16); more intensive grazing management (e.g., actively rotating cattle herds across pastures instead of letting them roam freely); and increases in meat production per animal (e.g., through improved breeds or better veterinary care) (Searchinger et al. 2019). Achieving these productivity gains does not require a shift to feedlot systems, which can reduce GHG emissions intensity per kilogram of beef versus production systems where cattle spend their entire lives on grass but also come with concerns regarding impacts on worker and community health (Chamanara et al. 2021), air and water pollution (Chamanara et al. 2021), antimicrobial resistance (Cameron and McAllister 2016), and animal welfare (Salvin et al. 2020).

BOX 16 | Silvopastoral systems in Ethiopia boost productivity and resilience

Much research and development on silvopastoral systems—which integrate trees and shrubs with grazing livestock—has focused on the use of these systems for climate change adaptation. In resource-limited areas with a high level of land degradation, such systems can provide a co-benefit of climate change mitigation, both through increased output of meat and milk per hectare (which can avoid additional land clearing as demand for livestock products grows) as well as an increase in carbon stocks in plants and soils. The productivity and environmental benefits and trade-offs of shifting to silvopastoral systems, however, depend on specific factors, including the current resource availability, the level of intensification, and/or the production system used.

Research and extension work developing a local tree species–based silvopastoral system using *Ficus thonningii* has produced compelling results in terms of productivity, livelihoods, climate change adaptation, and environmental resilience in Ethiopia. Introduction of *Ficus thonningii* silvopastures into degraded pasturelands in northern Ethiopia has enabled smallholder farmers to produce 500 percent more fodder per hectare of land, reduce costs incurred for expensive concentrate feeds by 50 percent (Balehegn et al. 2015, 2012; Mekuriaw and Asmare 2018), and reduce water use required for forage production by 83 percent (Balehegn 2017, 2012). The ficus tree's ability to provide shade and fodder, and other multipurpose benefits and qualities such as drought tolerance, has contributed to year-round fodder availability and improved animal health, leading to increased milk production and livestock weight gain, and positively impacting local farmers' livelihoods (Balehegn 2017).

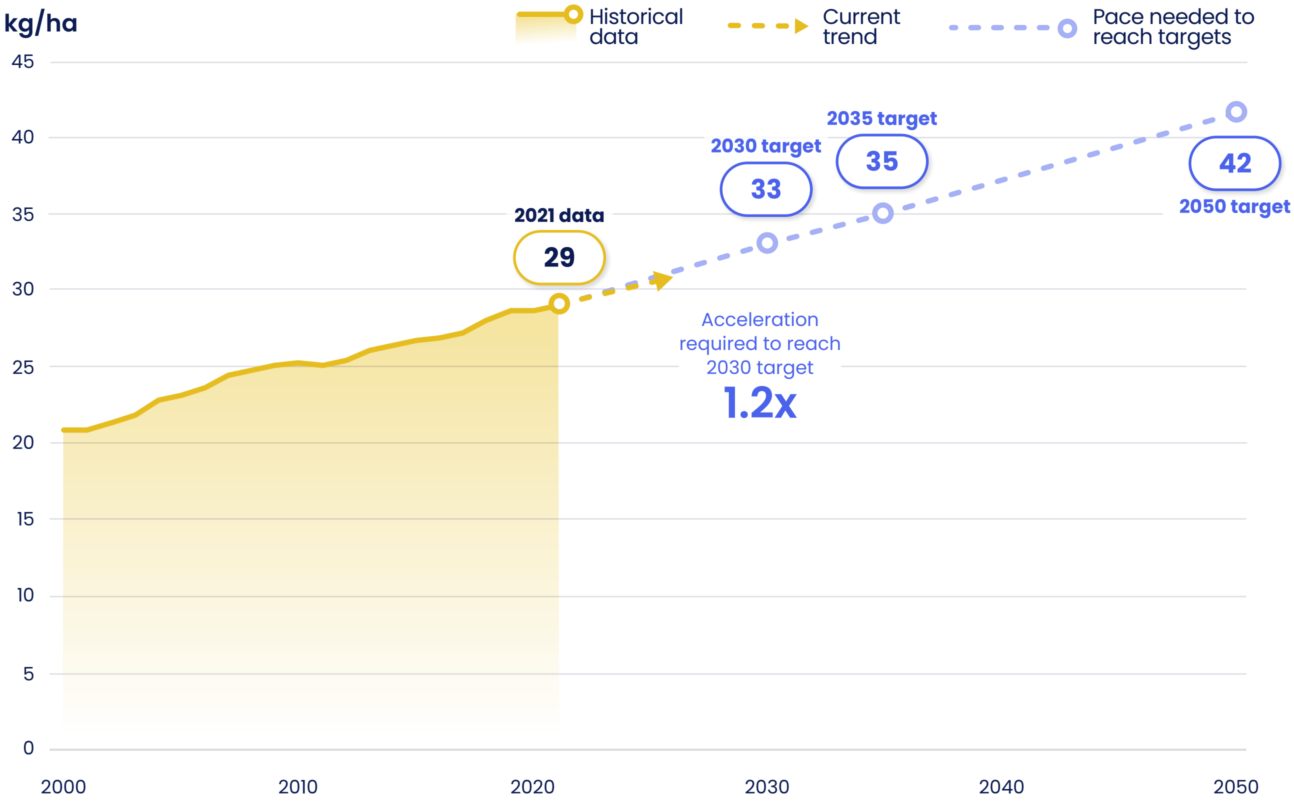
In addition to the direct benefits to livelihoods and livestock, the *Ficus thonningii* silvopastures play an important role in soil conservation and ecosystem restoration. Studies on degraded pasturelands and croplands indicated a 40 percent increase in soil carbon content in areas with the integration of *Ficus thonningii*, contributing to enhanced soil fertility and reduced soil erosion (Berhe et al. 2013), while habitat created by trees on degraded pasturelands enabled the return of bird species hitherto locally extinct in northern Ethiopia (Balehegn et al. 2016). The multiple adaptation and livelihood benefits have resulted in widespread adoption within Ethiopia and recognition of the *Ficus thonningii*–based silvopastoral system. More than 25,000 households in northern Ethiopia adopted this practice between 2010 and 2017, incorporating *Ficus thonningii* trees into degraded pasturelands and farmlands. The practice has been identified as a successful innovation by the Food and Agriculture Organization of the United Nations, the European Commission, and others (AFSA 2018; LD4D 2021; FAO 2021; Madsen and Wezel 2021).

To meet the 2030 target, ruminant meat productivity must improve by another 15 percent, which will require recent growth rates to accelerate by 1.2 times. So, while progress is heading in the right direction, it remains off track. Satellite-based evidence of deforestation (Goldman et al. 2020) also shows that 45 Mha of forest were replaced by pastureland for cattle grazing between 2001 and 2015, mainly in South America, suggesting that gross pasture expansion to meet growing global demand for ruminant meat has yet to stop. And total global ruminant meat production does continue to grow; according to FAOSTAT (2023), after a historical high in 2019 there was a one-year dip in production in 2020, and then a new historical high in 2021 of 93.1 million tonnes of beef, buffalo, sheep, and goat meat.

Because much of the world's pastureland is dry, sloped, or has highly variable rainfall—which all limit productivity—achieving the global 2030 productivity goal will require particular attention to improvements on suitable hectares of wetter pastureland, especially in the tropics, where productivity is relatively low (Searchinger et al. 2019; Herrero et al. 2013). There are ranches in Brazil that exemplify the types of productivity improvements discussed above—including increases in meat production per hectare of 30 to 270 percent (zu Ermgassen et al. 2018). Significant barriers, such as finance, stand in the way of achieving similarly high-productivity improvements elsewhere (Grunwald 2023).

FIGURE 57 | Historical progress toward 2030, 2035, and 2050 targets for ruminant meat productivity

Right Direction, Off Track **S-Curve Unlikely**



Notes: kg/ha = kilograms per hectare. See Jaeger et al. (2023) for more information on methods for selecting targets, indicators, and datasets, as well as our approach for assessing progress.

Sources: Historical data from FAOSTAT (2023); targets derived from Searchinger et al. (2019).

Reduce growth in demand for food

Beyond improvements to agriculture, keeping warming below 1.5°C will require reducing the projected growth in demand for land-intensive goods through both reduced food loss and waste and dietary shifts. All countries should reduce food loss and waste, although the magnitude and types of changes required vary across countries. Dietary shifts away from ruminant meat and other animal-based foods and toward plant-based foods, in contrast, should be concentrated within high-consuming regions like North and South America, Europe, and Oceania, where such shifts in consumption (and their associated impacts on global supply chains) can have the largest impacts on reducing both agricultural land demands and GHG emissions.

FOOD AND AGRICULTURE INDICATOR 4:
Share of food production lost (%)

- **Targets:** The share of food production lost declines 50 percent by 2030, relative to 2016, and these reductions are maintained through 2050.

FOOD AND AGRICULTURE INDICATOR 5:
Food waste (kg/capita)

- **Targets:** Worldwide per capita food waste is reduced by 50 percent by 2030, relative to 2019, and these reductions are maintained through 2050.

Globally, about one-third of food is lost or wasted between the farm and the fork (FAO 2011). Food loss occurs before food gets to market, during harvest,[81] storage, and transport to market; whereas food waste occurs at retail markets, restaurants, or in homes. Food loss and waste result in high economic losses, contribute to food insecurity in lower-income countries,

and represent a "waste" of agricultural land, water, and other agricultural inputs. Not surprisingly, this high level of waste results in significant GHG emissions. The IPCC (2019) included an estimate that food loss and waste accounted for 8–10 percent of global human-caused emissions in 2011, including GHG emissions from agricultural production, land-use change, energy use across food supply chains, and waste in landfills. And while fruits and vegetables make up the largest share of global food loss and waste by weight, animal-based foods account for about half of the GHG emissions associated with food loss and waste (Guo et al. 2020). Models have demonstrated how halving global food loss and waste rates has substantial mitigation potential and can help bring food system–related GHG emissions in line with pathways that limit warming to 1.5°C (Clark et al. 2020; IPCC 2022b), in addition to being aligned with Sustainable Development Goal Target 12.3 (United Nations 2015).

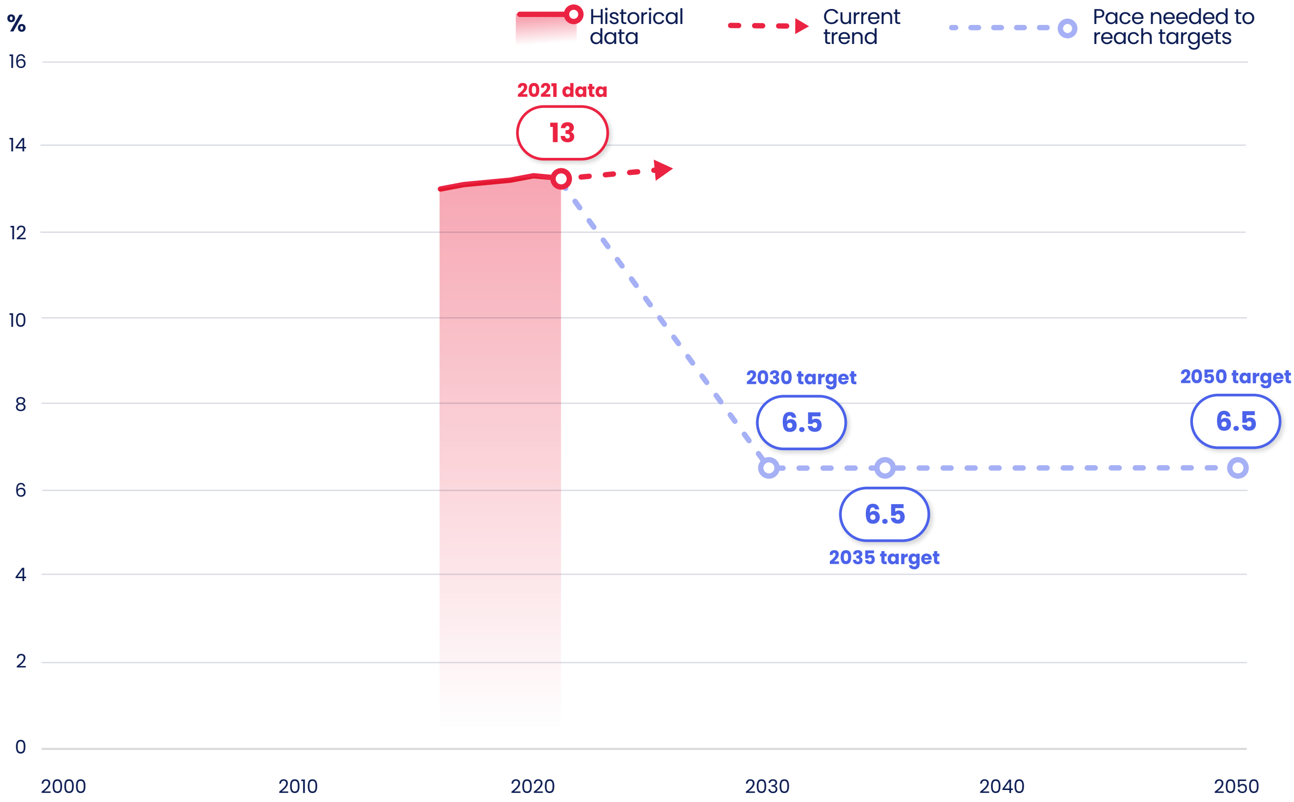
Global trend data through the Food Loss Index (FAO 2019) and Food Waste Index (UNEP 2021e) are just starting to become available. The most recent global estimates are that 13.2 percent of global food production was lost between the farm gate and processing stages of the food supply chain in 2021 (FAOSTAT 2023) (Figures 58 and 59), and that 17 percent of food at the retail level (or 121 kilograms per person per year) was wasted in households, food service, and retail in 2019 (UNEP 2021e) (Figure 60).

As for food losses, thanks to an update in July 2023, FAOSTAT now reports three years of data on the share of food production lost (2016, 2020, and 2021), providing the opportunity to begin seeing trends. Globally, the rate of food loss rose slightly from 13.0 to 13.3 percent between 2016 and 2020 and then declined slightly to 13.2 percent in 2021, meaning that global trends are still moving in the wrong direction for this target.

FIGURE 58 | Historical progress toward 2030, 2035, and 2050 targets for share of food production lost

Wrong Direction, U-turn Needed

S-Curve Unlikely



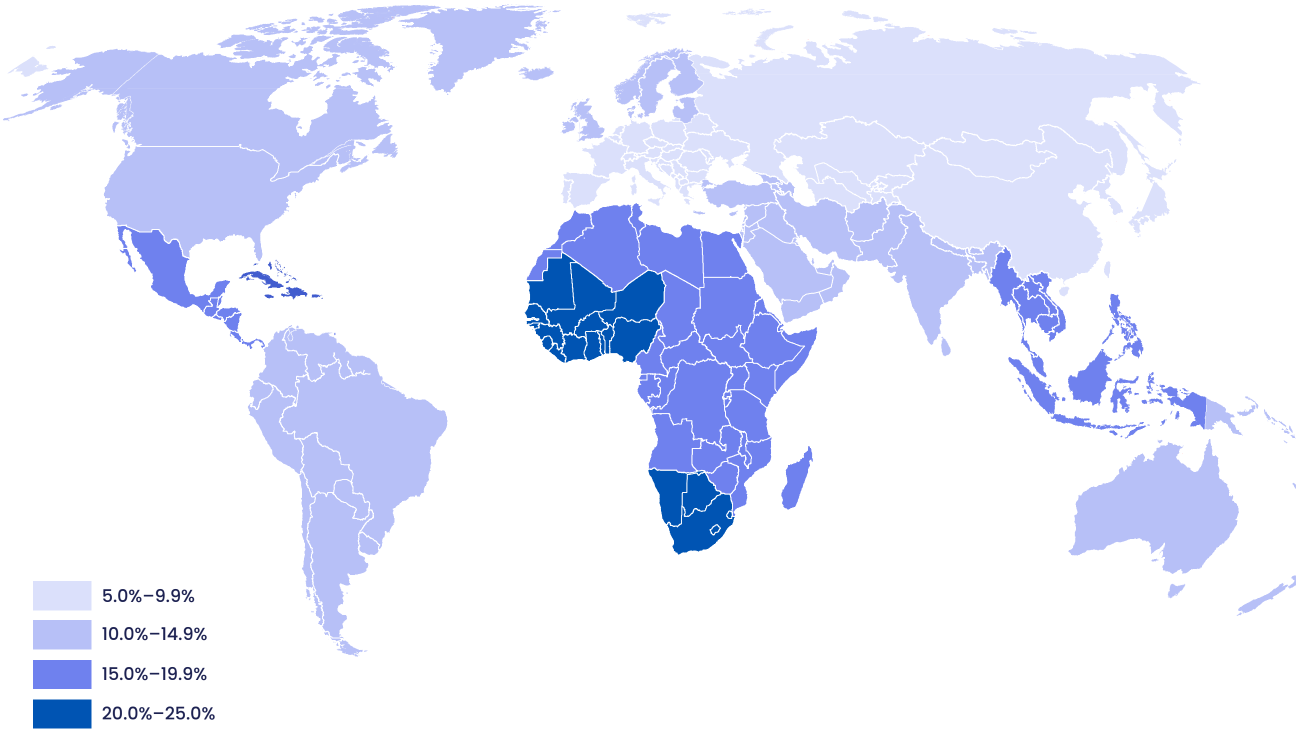
Notes: Food loss occurs before food gets to market. Also, due to data limitations, an acceleration factor was calculated for this indicator using a linear trendline estimated with three data points across six years. See Jaeger et al. (2023) for more information on methods for selecting targets, indicators, and datasets, as well as our approach for assessing progress.

Sources: Historical data from FAOSTAT (2023); targets from United Nations (2015).

The rate of food loss differs across subregions (Figure 59). On a positive note, subregions within sub-Saharan Africa have all made progress in reducing food losses between 2016 and 2021. By contrast, Northern Africa, all subregions in Europe, and most subregions in the Americas (except North America) saw increases in the share of food production lost between 2016 and 2021. While the results across world regions are mixed, overall, a dramatic step change is needed to move global trends in food losses in the right direction to halve them by 2030.

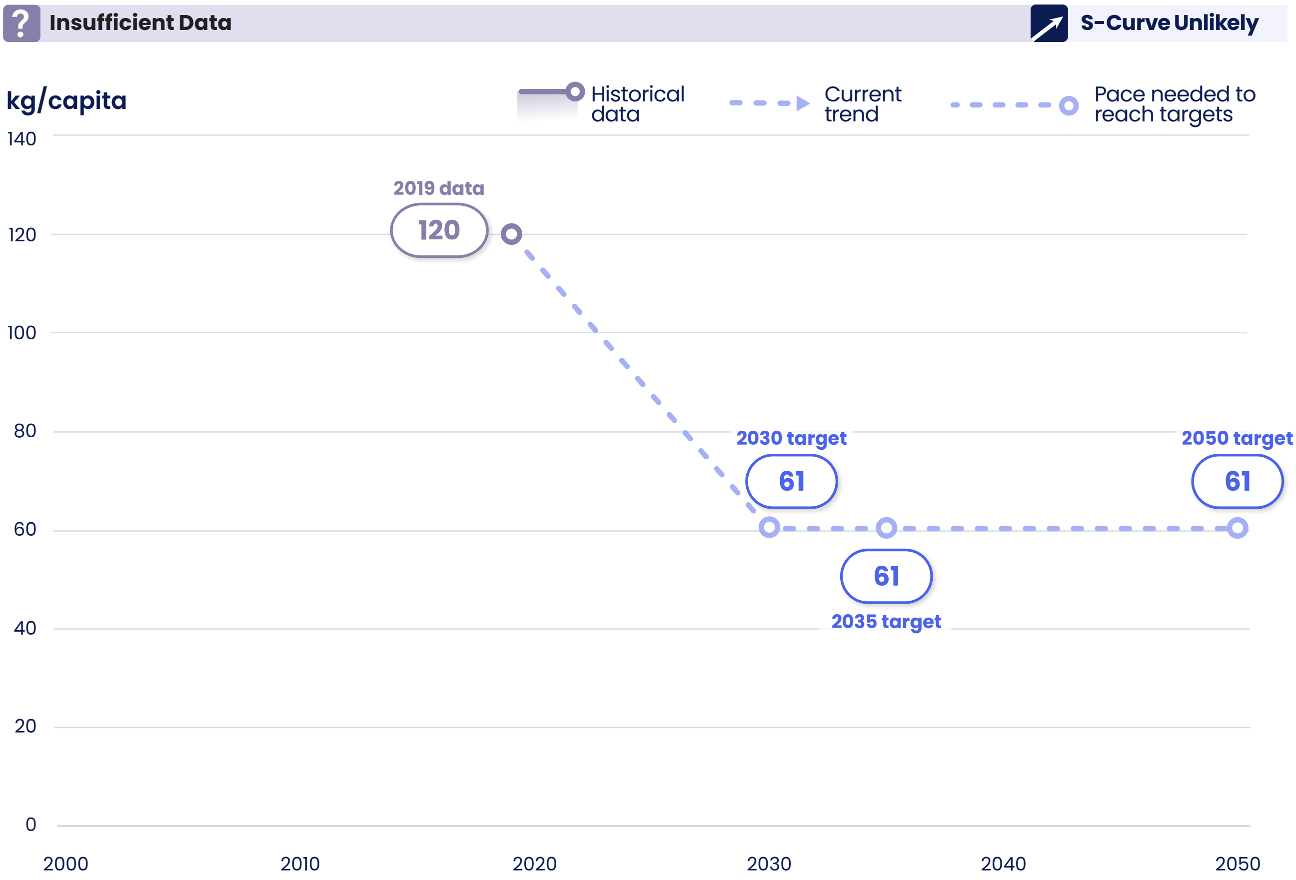
As for trends in food waste, because 2019 is the first and only year for which food waste estimates are available at the global level, data are insufficient to measure progress toward this indicator. Increasing the availability of data to measure food waste at retail, food service, and household levels is also necessary to better disaggregate differences at regional and country levels. Available evidence, however, suggests that substantial changes will be needed to meet the target of halving food waste. For example, in the United States, although the federal government set a goal in 2015 to reduce food loss and waste by 50 percent by 2030 and several U.S. states have adopted legislation aimed at reducing food waste, U.S. per capita food waste actually *increased* by 6 percent between 2016 and 2019, from 149 to 158 kilograms per person per year. The latest U.S. government status report (U.S. EPA 2023a) notes that some of the recent state food waste laws have yet to be fully implemented.

FIGURE 59 | Share of food production lost by subregion in 2021



Source: FAOSTAT 2023.

FIGURE 60 | Historical progress toward 2030, 2035, and 2050 targets for food waste



Note: kg/capita = kilograms per capita. Food waste occurs at the retail level and in homes and restaurants, among other locations. See Jaeger et al. (2023) for more information on methods for selecting targets, indicators, and datasets, as well as our approach for assessing progress.

Sources: Historical data from UNEP (2021e); targets from United Nations (2015).

FOOD AND AGRICULTURE INDICATOR 6:
Ruminant meat consumption (kcal/capita/day)

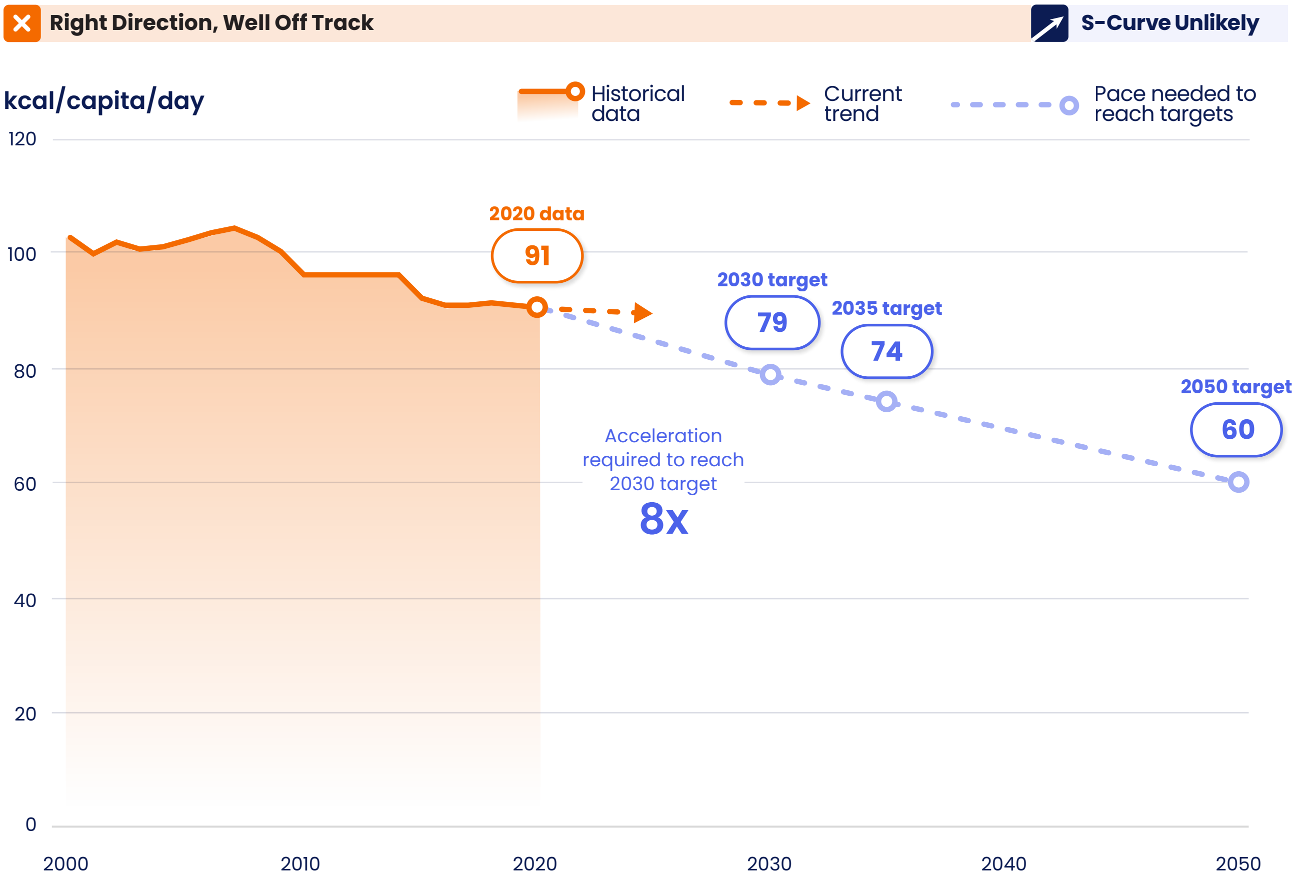
- **Targets:** Across high-consuming regions of the Americas, Europe, and Oceania,[82] daily per capita consumption of ruminant meats, including beef, lamb, and goat,[83] decreases to 79 kilocalories by 2030, 74 kilocalories by 2035, and 60 kilocalories by 2050.

As incomes rise and people move to cities, diets tend to become more varied and higher in resource-intensive foods like meat and dairy. For this reason, consumption of animal-based foods is projected to grow by nearly 70 percent between 2010 and 2050 (Searchinger et al. 2019), an estimate roughly in line with those from several other researchers (e.g., Springmann et al. 2016; Tilman and Clark 2014; Willett et al. 2019). This projected growth makes achieving ecosystem protection and climate mitigation goals more challenging: for instance, beef requires 20 times more land, and leads to 20 times more GHG emissions per gram of protein, than beans (Ranganathan et al. 2016). Beef and other ruminant meat production (e.g., lamb and goat) is also roughly seven times as land- and GHG-intensive as poultry and pork production (Ranganathan et al. 2016).

Animal-based foods are an important source of high-quality, bioavailable protein and micronutrients, especially during pregnancy and lactation, infancy and early childhood, and in some cases adolescence and aging (Beal et al. 2023). Modest increases in consumption of animal-based foods can boost nutrition in low-income countries while limiting the growth of environmental impacts (Kim et al. 2020; Willett et al. 2019). However, in high-income countries, where protein consumption is well above dietary requirements and substitutes for animal protein are widely available, shifting diets toward plant-based foods and especially away from ruminant meats can reduce agricultural land demand and GHG emissions (Sun et al. 2022).

After declining for several decades, per capita ruminant meat consumption across high-consuming regions (the Americas, Europe, and Oceania)[84] plateaued around 2016, falling by only 0.8 percent between 2016 and 2020 and hovering around 91 kilocalories per day during that

FIGURE 61 | Historical progress toward 2030, 2035, and 2050 targets for ruminant meat consumption



Notes: kcal/capita/day = kilocalories per capita per day. Consumption data are given in availability, which is the per capita amount of ruminant meat available at the retail level and is a proxy for consumption. Also, this diet shift applies specifically to the high-consuming regions (Americas, Europe, and Oceania). It does not apply to populations within the Americas, Europe, and Oceania that already consume less than 60 kcal/capita/day, have micronutrient deficiencies, and/or do not have access to affordable and healthy alternatives to ruminant meat. See Jaeger et al. (2023) for more information on methods for selecting targets, indicators, and datasets, as well as our approach for assessing progress.

Sources: Historical data from FAOSTAT (2023); targets from Searchinger et al. (2019).

time period (FAOSTAT 2023). This very slow rate of decline would need to accelerate eightfold to hit the 2030 target of 79 kilocalories per day (the equivalent of about two servings per person per week), on the way to the 2050 target of 60 kilocalories per day (about 1.5 servings per person per week) (Figure 61).[85]

Even within the high-consuming regions for which this target applies, there is considerable difference in per capita ruminant meat consumption. Per capita consumption in Australia and New Zealand (179 kcal per day) and South America (135 kcal per day) were double the rate of consumption in Europe (67 kcal per day) in 2020. Larger reductions will also be necessary in North America, which stood at 107 kcal per day in 2020.

While other regions remained far below the 60-kilocalorie threshold for ruminant meat consumption in 2020, including Africa at 39 and Asia at 37, certain countries (e.g., China) are experiencing significant increases and will likely reach the 60-kilocalorie threshold between now and 2050. Data from China show that beef and lamb consumption is twice as high in urban areas as in rural areas and that rising incomes generally lead to higher demand for all types of meat (Mao et al. 2016). In cases where per capita ruminant meat consumption is on the rise, it would be advisable to try to peak it early so as not to breach the threshold, and instead aim to shift demand to less GHG-intensive protein sources.

Recent developments across food and agriculture

Recent years have witnessed a wave of new multilateral commitments focused on transforming the food and agricultural sector to mitigate climate change, safeguard biodiversity, and ensure food security for all in a changing climate—a promising sign that the world's leaders are starting to recognize the significant contributions this sector can and must play in addressing these global crises. At COP26, for example, over 40 countries committed to making clean technologies the most affordable, accessible, and attractive options by 2030 under the Breakthrough Agenda, and a handful of these nations specifically pledged to make climate-resilient, sustainable agriculture the most attractive and widely adopted option for farmers everywhere by the end of this decade (IEA et al. 2022a). Over 140 countries also signed the Glasgow Leaders' Declaration on Forests and Land Use, pledging to implement and, if necessary, redesign agricultural policies and programs to incentivize sustainable agriculture, promote food security, and benefit the environment, among other goals (Prime Minister's Office 2021a). And 150 countries joined the Global Methane Pledge, under which they agreed to reduce methane emissions 30 percent by 2030—a goal that will require significant changes across the agricultural sector, which currently accounts for 40 percent of human-caused methane emissions (UNEP 2021h). Notably, however, some large agricultural economies like India and China have yet to sign this methane pledge. In addition, in December 2022, nearly 190 Parties to the Convention on Biological Diversity adopted the Kunming-Montreal Global Biodiversity Framework, agreeing to several targets focused on reducing the food and agriculture sector's impacts on biodiversity (CBD 2022a). While this increasing political attention on food and agriculture represents a welcome change, immediate actions, as well as substantial resources, will be needed to deliver on these commitments in time.

Recent developments in sustainably increasing agricultural productivity while reducing GHG emissions from agricultural production

No single technology or practice can boost productivity while reducing GHG emissions across all agricultural landscapes, which produce a range of crops and livestock products across diverse social, economic, and biophysical environments. This diversity challenges efforts to develop innovations for wide-scale adoption. New technologies that could play an important role in sustainably delivering the productivity gains needed, while lowering GHG emissions and minimizing other environmental harms, remain under development. Considerable investments in research, development, and deployment, then, are needed both to bring new technologies to market and to transfer agricultural practices that have been successful in one context to others.

Scientists are currently exploring two lines of innovation for reducing methane emissions from the digestive process of ruminant animals (e.g., cattle, sheep, goats)—a process referred to as "enteric fermentation."

The first involves developing feed additives that reduce emissions by interfering in the processes that generate methane, and the second aims to selectively breed animals that generate less methane during their digestion. Many additives are currently being tested, as the primary challenge is that, while some deliver productivity benefits, others have potential side effects (e.g., on animal health). The most approved and commercially available additive is 3-Nitrooxypropanol (3-NOP), which provides average reductions of enteric methane reduction up to 30 percent depending on animal type, diet, and dose (Yu et al. 2021; Mulhollem 2023). In 2021 the European Union approved it for commercial use as part of its Farm to Fork strategy, joining Australia, Brazil, and Chile (DSM 2022). While it is not yet approved for commercial use in the United States, U.S. lawmakers introduced the bipartisan Innovative Feed Enhancement and Economic Development (FEED) Act in 2023, which would create a new federal approval pathway for novel feed additives such as 3-NOP (Reus 2023). Additional long-term research is needed to fully understand side effects, suitability for different production systems, and long-term trade-offs in and/or co-benefits to livestock productivity before they can be widely utilized (Beauchemin et al. 2022; Hegarty et al. 2021; Readfearn 2023). Breeding animals for reduced enteric methane emissions has also received considerable research attention in recent years, but low-emitting breeds with equal or better productivity and resilience than current breeds are yet to be developed at scale. In New Zealand, for example, researchers have bred lower-methane sheep that emit about 12 percent less methane than their high-emitting counterparts, with no significant impact on productivity (Rowe et al. 2019), and the first breeding material with a low-methane genetic trait went on the market in 2023 (Nickel 2023). Ongoing research initiatives are collecting and analyzing genetic data related to high- and low-emitting cows to facilitate future breeding efforts (Stepanchenko et al. 2023).

Most mitigation potential from rice production rests in Asia, where 90 percent of global rice production occurs (FAOSTAT 2023). Rice methane emissions occur in flooded rice fields where water limits oxygen penetration into the soil, allowing microorganisms called archaea that produce methane to thrive. Boosting rice yields per hectare (which minimizes the need to flood additional areas) and optimizing water management (which reduces the amount of time a field is flooded) can both reduce emissions. Research in this area is ongoing; for example, studies in Indonesia from 2020 to 2022 found that improved water management was able to reduce methane emissions by 70 percent, while boosting rice yields and reducing pesticide and fertilizer runoff (Turrell 2023).

Nitrous oxide emissions related to soil fertilization (including both nitrogen fertilizer and manure application) can be significantly reduced in many places by increasing nitrogen-use efficiency and reducing overuse of chemical fertilizer. Doing so can also reduce water pollution, since less nitrogen leaches into the water (Gao and Cabrera Serrenho 2023), and can also boost yields. Innovations to address this include precision application of fertilizers, which uses field productivity data from drones or satellites. Another innovation for reducing N_2O emissions is controlled-release fertilizers, which slowly release nutrients over time. These fertilizers have been commercialized but currently represent only a small share of synthetic fertilizer sales. Recent innovations in controlled-release systems, such as the use of low-cost coatings, demonstrate the potential to reduce the environmental impact of conventional fertilizers and enhance nutrient use efficiency. The findings underscore reduced environmental harm and improved nutrient utilization, crop yields, and cost-effectiveness (Mansouri et al. 2023; Liang et al. 2023b). Uncertainty among farmers about these fertilizers' benefits—which can vary depending on product formulation, soil, temperature, and other conditions—and lack of research into scaling up use of these fertilizers may be constraining factors (Searchinger et al. 2019; Ferguson et al. 2019).

New initiatives are aiming to accelerate reduction of agricultural production emissions and build sustainable productivity gains. For example, the Agriculture Innovation Mission for Climate (AIM for Climate) is seeking to increase investment in research, development, and demonstration (RD&D) to accelerate innovation through many of the potential mitigation practices described above and has grown to become a coalition of over 400 partners, including 47 countries. Launched by the governments of the United States and United Arab Emirates at COP26 in 2021, its members have raised more than $8 billion as of early 2023 and have announced 30 "innovation sprints." These "sprints" focus on enteric methane, boosting productivity and resilience on cropland and pastures, optimization of nitrogen use, smallholder soil fertility management, agroforestry, rice production, and alternative proteins, among others, each with budgets of between $1 million and $500 million (AIM for Climate 2023). Another example globally relevant to the private sector is the 2022 release of guidance by the Science Based Targets initiative (SBTi) detailing how companies should set mitigation targets to reduce emissions from the forest, land, and agriculture (FLAG) sectors. Land-intensive companies working with SBTi were required to start setting FLAG targets in line with a 1.5°C pathway beginning in 2023 (Anderson et al. 2022). Finally, to truly scale RD&D, finance, knowledge, and technology transfer will be needed. The Food and Agriculture for Sustainable Transformation Initiative, launched at COP27 and facilitated by FAO, aims to increase countries' access to climate finance and investment related to agriculture and food systems, improve knowledge and capacity related to climate-smart food systems, and strengthen the inclusion of agriculture and food systems across climate change policies (FAO 2022a).

Linking yield improvements with ecosystem protection is an effective strategy to maximize land-based carbon stocks while meeting growing demand for land-based products (Williams et al. 2018). These links can be in the form of land-use planning and zoning, financial instruments (e.g., agricultural loans or subsidies that are conditioned on achieving environmental or conservation goals), and initiatives or policies where agricultural commodity purchasers and traders commit to sourcing products that are deforestation- and conversion-free (Searchinger et al. 2019). One recent example of such a policy is the EU regulation on deforestation-free products that entered into force in June 2023 (European Commission n.d.b.). While demand-side deforestation-free commitments have had only limited effectiveness so far, they have led to increased monitoring and transparency in supply chains (Lambin and Furumo 2023). To be successful, a variety of complementary supply- and demand-side approaches are needed (Lambin and Furumo 2023), accompanied by strong governance and enforcement of forest protection laws (Garrett et al. 2019).

Recent developments in reducing food loss and waste

The "Target-Measure-Act" approach can help guide efforts to reduce food loss and waste. Despite being halfway through the implementation of the Sustainable Development Goals launched in 2015, with goals set for 2030, progress is lagging on the adoption of target-setting in both the public and private sector. Between 2019 and 2021, just one new country (Argentina) set targets in line with the SDG Target 12.3, meaning that about 55 percent of the world's population is now represented by governments with food loss and waste targets (Lipinski 2022). An additional seven of the world's 50 largest food companies set food loss and waste targets during that period, bringing the total number of companies with food loss and waste targets to 39 (including all of the retailers within the 50 largest companies) (Lipinski 2022).

While setting targets can help establish ambition and guide subsequent policies and actions, measuring food loss and waste is not only critical to monitor progress toward these targets but also to help understand where actions are proving effective (or not) in reducing food loss and waste. Unfortunately, few countries systematically measure food loss and waste throughout the supply chain according to the latest available data. Between 2019 and 2021, only seven governments began measuring their food loss and waste, bringing the total to 19 countries representing 12 percent of the global population (Lipinski 2022). These countries included Argentina, Australia, Canada, Colombia, Denmark, Israel, Italy, Japan, Finland, Mexico, the Netherlands, New Zealand, Norway, Saudi Arabia, Slovenia, Spain, Sweden, the United Kingdom, and the United States. The UN agencies' efforts to monitor progress at the global level through the Food Loss Index (FAO 2019) and Food Waste Index (UNEP 2021e) provide standard methods for governments to measure food loss and waste in order to increase country-level data over time. Compared to governments, a higher proportion of the world's largest companies have been making progress in terms of measuring and reporting their food loss and waste; 4 more of the 50 largest food companies began measuring and reporting between 2019 and 2021, bringing the total to 19 companies, 10 of which are engaging with their suppliers to reduce waste (Lipinski 2022).

Lastly, while setting targets and measuring progress are essential, reducing food loss and waste at a meaningful scale will require numerous actions across food supply chains (Flanagan et al. 2019). Governments and companies can lead in motivating such actions, though producers, citizens, and other actors will also play important roles in advancing progress. On a promising note, the number of countries implementing such actions has increased substantially, from countries representing 14 percent of the global population at the end of 2018 to countries representing 35 percent of the global population by the end of 2021. An encouraging recent example of country-level action is in China, where the government passed a wide-ranging law in 2021 to reduce food waste at the consumer level, including fines for food service establishments with excessive food preparation, joining the few countries with measures to enforce food waste reduction (Shen et al. 2023). In July 2023, the European Commission also proposed legally binding targets for member states to achieve a 10 percent reduction in food losses in processing and manufacturing and 30 percent per capita reduction in retail and household waste by 2030 (European Commission 2023g). Although the European Commission's proposed targets are still under negotiation and are less ambitious than SDG Target 12.3, they illustrate progress toward legally requiring food loss and waste reductions. Companies have also been scaling up actions to reduce food loss and waste, with the number of companies with established food loss and waste programs having grown from 11 at the end of 2018 to 29 by the end of 2021. Notably, Ingka Group (IKEA's largest retailer) was the first company in the world to successfully halve food waste, achieving this reduction between 2017 and 2021 (Ingka Group 2022).

While it is encouraging that both public and private sector decision-makers have begun making commitments and taking action to reduce food loss and waste, measurable global decreases in the next few years will require rapidly increasing the adoption of new technologies, such as innovative storage systems and technology to slow the ripening of produce, and other interventions, such as changes to date labels, reduced portion sizes, facilitation of the donation of unsold food, and food waste diversion laws. Increased financial services (e.g., affordable access to credit) for producers in the Global South, as well as modifying incentives (e.g., subsidies) to reduce food loss and waste in the Global North, are potential ways to accelerate progress (Cattaneo et al. 2021; World Bank 2020).

Recent developments in advancing dietary shifts in high-consuming regions

The importance of shifting diets as a climate mitigation solution is also beginning to enter international climate policy conversations. For their Race to Zero and Race to Resilience campaigns, the United Nations Climate Change High-Level Champions have set an even more ambitious target than this report, calling for 40 percent of the global population to shift to culturally appropriate versions of the Planetary Health Diet by 2030, as described by the EAT-Lancet Commission (Falk et al. 2020; High-Level Champions n.d.; Willett et al. 2019). The Planetary Health Diet focuses on numerous changes to current dietary patterns—in addition to reducing ruminant meat consumption—with a goal to optimize multiple health and sustainability outcomes (Willett et al. 2019). While the United Nations Climate Change High-Level Champions represent nonstate stakeholders, their priorities signify increasing pressure on governments to address them. This pressure is important given that, as of September 2022, only 5 out of 134 countries' updated NDCs included measures for shifting to sustainable and healthy diets, compared to 94 countries that included mitigation measures for agriculture (WWF 2022).

Both the public and private sector have a significant potential to shift food consumption through influencing the availability, affordability, convenience, and desirability of different foods (Herforth and Ahmed 2015). Governments can improve policies and regulations—such as national dietary guidelines—that influence food production and consumption patterns to make them more compatible with climate and other environmental goals (Springmann et al. 2020). The Danish government, for example, released updated dietary guidelines in 2021 that considered the climate impact of foods for the first time; the guidelines included recommendations to increase legume and vegetable consumption and to reduce meat consumption (Food Nation n.d.). Public and private institutions can also use their purchasing power to procure food that is both healthier and lower in emissions (Swensson and Tartanac 2020). For example, a collection of more than 60 leading food service providers under the Coolfood initiative have made some promising progress using a combination of collective target-setting, monitoring of progress, and application of behavioral science "nudges" (Box 17). And while policy efforts at the national level have been relatively limited,

BOX 17 | Shifting to more sustainable diets in food service

The Coolfood Pledge, launched in 2019, helps large food providers (including restaurant chains, contract caterers, city governments, universities, and hospitals) measure and reduce the climate impact of the food they serve. Members of the pledge commit to collectively reducing their food-related GHG emissions by 25 percent by 2030. Each year, they report their annual food purchases to track GHG emissions over time, and they use behavioral science to shift their food offerings in a more plant-forward, climate-friendly direction while maintaining customer satisfaction. Most members are based in the Americas, Europe, and Oceania, where per capita meat consumption is high, but several are based in Asia as well. As of 2023, the Coolfood initiative includes more than 60 members.

The Coolfood Pledge's early adopters, a cohort of nearly 50 members including large organizations like IKEA and serving nearly a billion meals per year, have reduced their food-related GHG emissions intensity per 1,000 kcal by 10 percent through 2022, relative to a 2015–18 baseline (Cho and Waite 2023) (Table 8).[86] City, university, and health care members have reduced emissions intensity the fastest, ahead of the pace needed to hit the 2030 target shown in Indicator 1. Restaurants and corporate campuses are also making progress but at a slower pace. This progress has come about through a shift away from ruminant meats, and other animal-based foods, and toward plant-based foods (Table B17.1).

TABLE B17.1 | Coolfood Pledge member progress by sector through 2022

SECTOR	NUMBER OF MEMBERS SUBMITTING DATA	CHANGE IN GHG EMISSIONS PER 1,000 KCAL THROUGH 2022 (%)
City	5	-24
Company	10	-4
Healthcare	23	-21
Restaurant	4	-7
University	6	-19
Total	**48**	**-10**

Notes: GHG = greenhouse gas; kcal = kilocalorie. Data shown for members who joined the Coolfood Pledge prior to 2022.

Sources: Coolfood member food procurement data from Cho and Waite (2023). GHG emissions calculations based on Poore and Nemecek (2018); and Searchinger et al. (2018).

BOX 17 | Shifting to more sustainable diets in food service (continued)

Several enabling conditions have contributed to Coolfood's early success. As a target-setting and action initiative, Coolfood relies on leadership from private and public sector food providers. These leaders commit to an ambitious collective climate target, and some, like New York City with a 33 percent reduction target by 2030, commit to even more ambitious individual targets. Members then think through measures to help shift consumer demand toward low-carbon foods within their dining establishments. They draw from recent behavioral research, such as the Playbook for Guiding Diners toward Plant-Rich Dishes in Food Service (Attwood et al. 2020) and plan and test interventions through a structured process each year. Some members have seen success incorporating innovative plant-based meat and dairy alternative ingredients into favorite meals. Some Coolfood members, like U.S.-based restaurant chain Panera, have incorporated ecolabeling and direct consumer engagement into their strategy, putting a Coolfood badge symbol indicating which meals are low-carbon directly on menus, both in stores and in their online ordering app. Over time, the Coolfood initiative aims to shift social norms and demonstrate that climate action can and must be delicious.

Notes: GHG = greenhouse gas; kcal = kilocalories.

the rise of the Milan Urban Food Policy Pact launched in 2015 and now signed by more than 200 cities (MUFPP 2023) and the C40 Cities Good Food Cities Accelerator launched in 2019 and now signed by 16 cities (C40 Cities 2023) have demonstrated the leadership role that municipalities can play in advancing more sustainable and climate-friendly food systems. More recently, the Food for the Planet campaign in the United Kingdom launched in 2021 with a toolkit of suggested policies, planning, and other actions for local councils to drive action on food, climate, and nature; since then, more than 50 localities have completed actions recommended in the toolkit (Sustainable Food Places 2023). And in 2023, the U.S. Conference of Mayors passed a resolution to support a shift toward more plant-based diets to address chronic disease, climate change, and financial sustainability (U.S. Conference of Mayors 2023).

While policies and interventions to encourage consumers to shift toward more plant-rich diets are needed to achieve climate goals and improve human health, advancing—and sustaining—dietary behavior changes is challenging, with limited progress made thus far. Replacing or reducing ruminant meat in people's diets with alternative proteins that provide a similar experience to meat and dairy but are sourced from plants, fungi, or through tissue culture represent one promising route to lowering ruminant meat consumption while reducing the behavior-change challenge. Compared to ruminant meat, plant-based meat substitutes, fermentation-derived microbial proteins, and (when produced using renewable energy) cultivated meats could all contribute to substantial reductions in GHG emissions and most other harmful environmental impacts (Bryant 2022; Humpenöder et al. 2022; Santo et al. 2020; Sinke et al. 2023). Plant-based meat substitutes have been on the market in high-income countries for several years. Although their sales have been growing, most remain more expensive than their animal-based counterparts and their market share has remained relatively small; for example, it increased from 1 percent in 2019 (GFI 2020) to 1.3 percent 2022 in the United States (GFI 2023c). Cultivated meat, which is meat produced by in vitro cultures of animal cells, is now being sold in limited quantities in two countries (Singapore and the United States), starting the first wave of commercialized products following regulatory approval in 2020 and 2023, respectively (GFI 2023b; Huling 2020). It is not clear, however, how financially viable cultivated meat will be for widespread adoption. The cost of producing cultivated meat is currently estimated at between $150 and $22,423 per kilogram (Vergeer et al. 2021), with different studies projecting its potential to decrease to $6.43–$116 (Vergeer et al. 2021), $17–$35 (Negulescu et al. 2023), and $63 (Garrison et al. 2022) per kilogram at the commercial scale, compared to a wholesale price of $8.75 per kilogram for conventional beef in 2022 (USDA 2023). More affordable cell culture media and bioreactor design are key challenges to overcome to achieve these price reductions (Garrison et al. 2022; Negulescu et al. 2023). Public spending to support R&D and commercialization for alternative proteins has been steadily increasing—more than doubling to reach $635 million in 2022 alone (GFI 2023a). At the same time, these investments will need to scale up substantially for alternative proteins to reach taste and price parity with animal-based meat and achieve widespread consumer acceptance, with one analysis estimating that global public spending will need to increase to $10.1 billion per year (Vivid Economics 2021). Interventions to influence social norms and increase positive feelings about different alternative proteins may also promote acceptance (Onwezen et al. 2021).

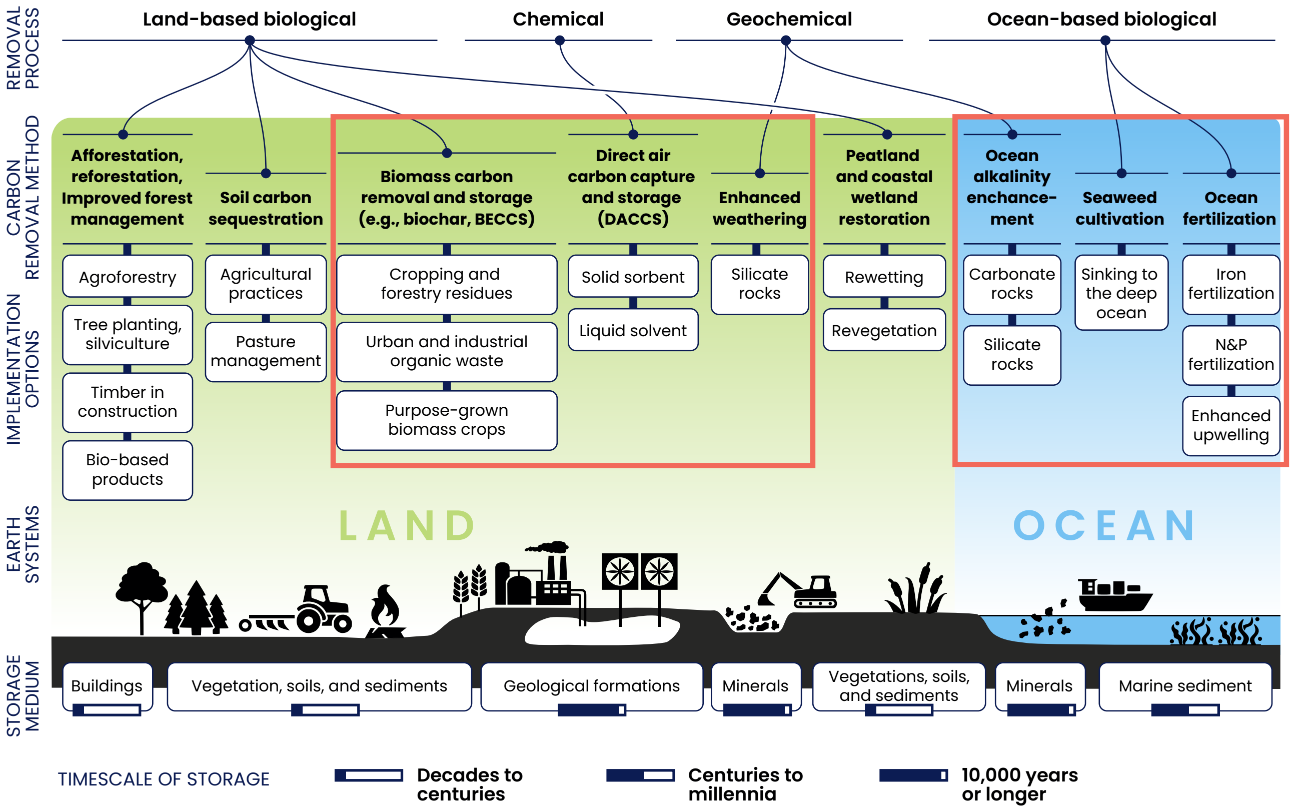
SECTION 8

Technological Carbon Removal

As a complement to deep and rapid emissions reductions, all pathways that limit warming to 1.5°C also rely on carbon dioxide removal (CDR, also hereafter referred to as carbon removal),[87] including nature-based approaches and technological carbon removal methods (IPCC 2022b). These approaches are needed to remove excess CO_2 in the atmosphere to stay within the carbon budget available for limiting temperature rise to 1.5°C. In the years leading up to the middle of the century, carbon removal can counterbalance GHG emissions for which abatement technologies do not become available (e.g., some heavy industry, non-CO_2 emissions from agriculture).[88] In the longer term, carbon removal can help reduce atmospheric CO_2 concentrations closer to preindustrial levels (Honegger et al. 2021; Bergman and Rinberg 2021).

Carbon removal includes a range of activities, from nature-based approaches like reforestation, peatland rewetting, and mangrove restoration to more technological approaches, such as direct air capture (DAC), carbon mineralization, and biomass carbon removal and sequestration (Figure 62, Box 18). Only these newer, technological approaches are covered in this section, while nature-based approaches are covered in Section 6, Forests and Land. Note that "technological" does not perfectly describe the types of carbon removal covered in this section, which include approaches that are novel and not yet providing large-scale removal, and in some cases are combinations of technological and biological or natural approaches.

FIGURE 62 | Range of carbon removal approaches on land and in the ocean

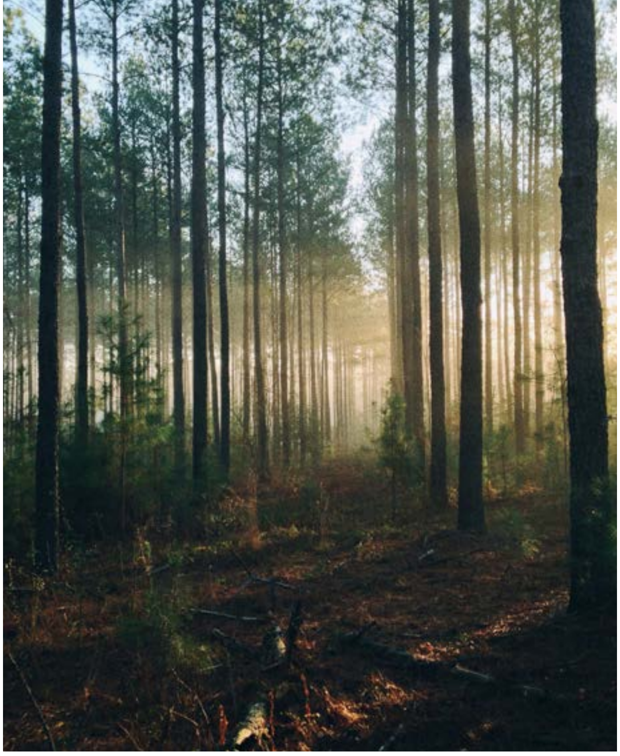


Notes: BECCS = bioenergy with carbon capture and sequestration; N&P = nitrogen and phosphorus. Approaches outlined in red are considered in this section. Those not outlined in red are considered in Section 6, Forests and Land.

Source: IPCC (2022b).

Some carbon removal technologies are ready for deployment, but many require further development or demonstration to improve processes and reduce costs and/or research to resolve uncertainties and potential risks (Fuss et al. 2018; Smith et al. 2023; NASEM 2019). And they all include trade-offs that will need to be evaluated on a case-by-case basis, taking local impacts and concerns into account.

Developing a robust portfolio of approaches can help in reducing costs, minimizing risks, and balancing the trade-offs associated with any one solution (Mulligan et al. 2020; Rueda et al. 2021). A portfolio that includes only nature-based approaches, for instance, faces constraints on land area availability and uncertainty around permanence (i.e., trees sequestering carbon can be cut down or burn in a wildfire). At the same time, a technology-only portfolio would be more costly and lack many of the co-benefits that natural approaches



BOX 18 | Options for technological carbon removal

The following technological carbon removal approaches are included in some, but not all, model scenarios analyzed by the IPCC; some (e.g., direct air capture and bioenergy with carbon capture and storage) must be combined with permanent sequestration to result in removal, while others, such as carbon mineralization, include permanent sequestration in their capture process.

Direct air capture (DAC): Direct air capture involves machines that use chemicals that selectively react with carbon dioxide in the air; the carbon dioxide can then be stored permanently. As of July 2023, there are 27 DAC plants globally; the largest one today removes 0.004 $MtCO_2$/yr and is powered by geothermal energy in Iceland (IEA 2023q). High cost, in part due to energy needs, is a major barrier to more rapid scale-up of direct air capture, but cost is expected to decline as more projects provide learning and optimization opportunities (NASEM 2019; Lackner and Azarabadi 2021). Tonnes of CO_2 removed by DAC have sold for around \$300/tCO_2 to more than \$2,000/tCO_2 on voluntary markets (Höglund 2022).

Biomass carbon removal and storage (BiCRS): BiCRS approaches use biomass to capture carbon dioxide through photosynthesis and then store that biomass underground. In some cases, the biomass is converted before it is sequestered using thermochemical or biochemical pathways. Scaling up biomass-based pathways faces barriers and challenges, including accessing biomass feedstocks that avoid negative or unintended impacts on biodiversity, agricultural production, and livelihoods and that result in overall net emissions reductions. Bioenergy with carbon capture and sequestration, a type of BiCRS, shows up most in climate model scenarios among technological carbon removal methods. Tonnes of biomass-based carbon removal have sold for less than \$100/tCO_2 to more than \$600/tCO_2 on voluntary markets (Höglund 2022).

Carbon mineralization: Carbon mineralization is a set of approaches that accelerate the natural reactions between some types of minerals and carbon dioxide, resulting in solid carbonates that lock away carbon. Further research will be needed to identify optimal application parameters (e.g., mineral type, location, particle size), understand ecological and environmental impacts (especially for ocean-based approaches), and develop robust monitoring and verification approaches (Sandalow et al. 2021). Tonnes of mineralization-based carbon removal have sold for \$75/tCO_2 up to more than \$1,300/tCO_2 on voluntary markets (Höglund 2022).

Notes: IPCC = Intergovernmental Panel on Climate Change; $MtCO_2$/yr = million tonnes of carbon dioxide per year.

can provide for resilience and biodiversity. For example, DAC is energy-intensive but uses comparatively little land and, when coupled with geologic sequestration, results in permanent storage; tree planting provides many co-benefits but requires comparatively more land and can be reversable (e.g., through wildfires); and some ocean-based approaches have large theoretical potential but many ecological and governance uncertainties (Lebling et al. 2022b).

The amount of carbon removal ultimately required to avoid intensifying climate impacts is inversely proportional to the speed and scale of emissions reduction—the more emissions reductions there are in the near term, the less carbon removal will be needed to reach global climate goals (Prütz et al. 2023). Climate modeling scenarios analyzed by the IPCC show a wide range of reliance on technological carbon removal methods (IPCC 2018, 2022b). However, the IPCC's assessment includes some scenarios that may use unsustainable amounts of land for biomass feedstock production and notes that dependence on carbon removal can be significantly reduced where resource efficiency, sustainable development, and/or low future energy demand are prioritized (IPCC 2022b). The targets laid out in this report use the IPCC's scenarios for how much carbon removal is needed to stay below 1.5°C with no or low overshoot, with filtering to only include scenarios that meet sustainability constraints; namely, restricted reliance on bioenergy with carbon capture and storage (BECCS). The target range is then set based on the 5th to 95th percentile of the range of technological carbon removal needed in these filtered scenarios. Carbon removal technologies provide 30–690 $MtCO_2$ of removal per year by 2030; by 2050, ranges span from 740 $MtCO_2$ per year to 5,500 $MtCO_2$ per year. Achieving even the lower end of the 2030 target would require scaling up more than 65-fold from today's level of removal.

Such scale-up will need to be implemented in a way that prioritizes equity and does not replicate the past harms that large-scale infrastructure build-out has inflicted on communities. For instance, in the United States, environmental burdens such as pollution from industrial facilities have long fallen disproportionately on low-income communities and communities of color (Skelton and Miller 2016). Questions that need to be answered include how to fairly share the responsibility of deploying carbon removal among countries and over time (Fyson et al. 2020; Lebling et al. 2023); how to identify carbon removal project sites and configure projects so that they do not disproportionately burden vulnerable communities and can provide local benefits; how to consistency and credibly quantify, transparently share, and verify information on removals; and whether and how carbon removal projects can leverage skills and expertise of jobs lost in the fossil fuel sector (e.g., from coal mining to mining rocks for carbon mineralization).

Global assessment of progress for technological carbon removal

A key indicator for tracking progress toward the scale-up of technological carbon removal is identifying how many tonnes of CO_2 have been captured from the air by carbon removal technologies and sequestered permanently (Table 8). To meet this definition of technological carbon removal, CO_2 must be captured from the atmosphere rather than at a point source like a cement plant.[89] Then it must be sequestered permanently[90]—for example, through storage in deep underground geological formations or the creation of stable carbonate minerals—or stored in durable products, such as concrete.

TABLE 8 | Summary of global progress toward technological carbon removal target

INDICATOR	MOST RECENT DATA POINT (YEAR)	2030 TARGET	2035 TARGET	2050 TARGET	TRAJECTORY OF CHANGE	ACCELERATION FACTOR	STATUS
Technological carbon removal ($MtCO_2$/yr)	0.57 (2022)	30–690	N/A	740–5,500	↗	>10x	✗

Notes: $MtCO_2$/yr = million tonnes of carbon dioxide per year. See Jaeger et al. (2023) for more information on methods for selecting targets, indicators, and datasets, as well as our approach for assessing progress.

Sources: Historical data from U.S. EPA (2023b); Climeworks (2021); and Höglund (2022); targets derived from IPCC (2022c); and Fuss et al. (2018).

TECHNOLOGICAL CARBON REMOVAL INDICATOR 1:

Technological Carbon Removal ($MtCO_2$/yr)

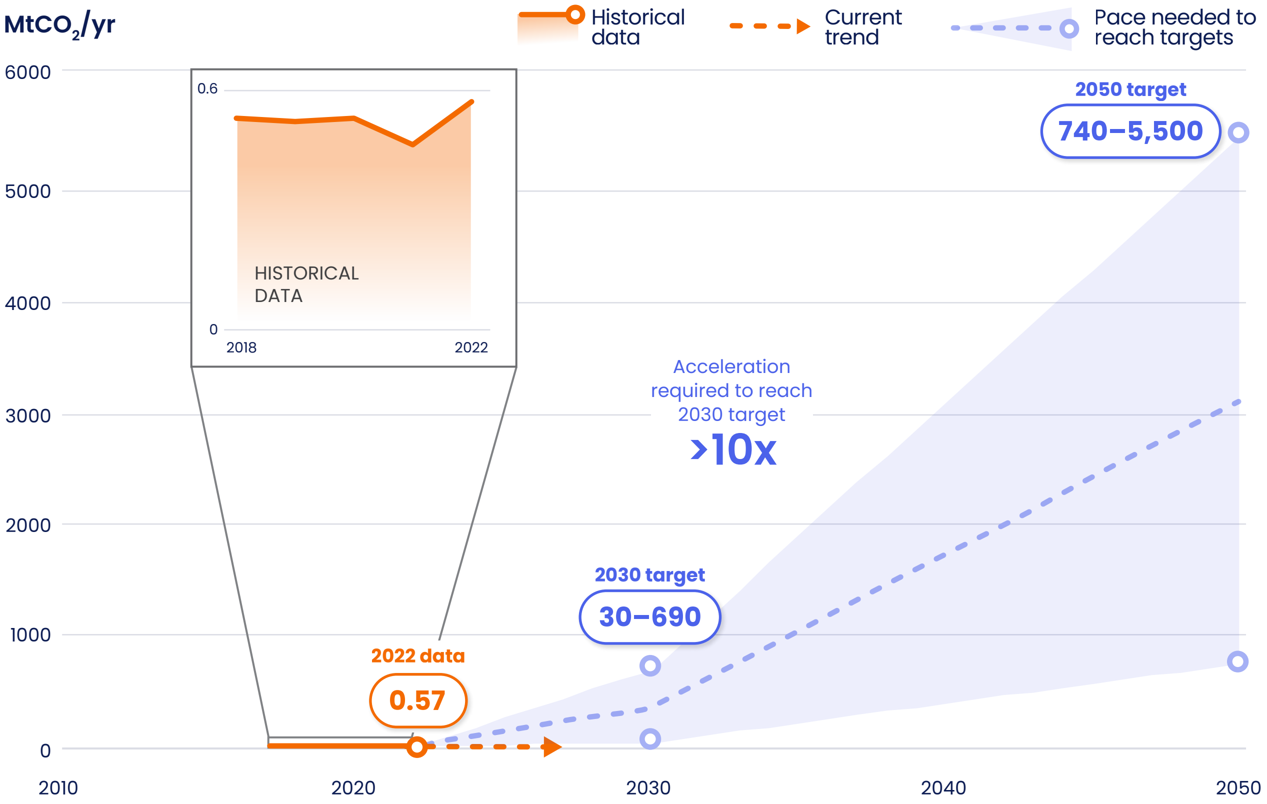
- **Targets:** The annual rate of technological carbon removal reaches 30–690 million tonnes of carbon dioxide per year ($MtCO_2$/yr) by 2030 and 740–5,500 $MtCO_2$/yr by 2050.

Assessing progress of carbon removal scale-up is difficult, as no centralized or comprehensive database tracks removal rates across technologies and approaches, and not all data around direct purchases of carbon removal credits are made public. Considering progress for each technology and then for purchases of carbon removal credits within voluntary markets can help provide a sense—albeit an incomplete one—of where technological carbon removal scale-up stands. Today less than 1 $MtCO_2$/yr comes from technological carbon removal.

- DAC capacity is around 0.008 $MtCO_2$/yr (IEA 2022d), but only around half of that captured CO_2 is stored permanently, namely through the 0.004 $MtCO_2$/yr Orca DAC plant in Iceland run by the Swiss company Climeworks. Other smaller DAC projects may be sequestering CO_2 as well, but they do not publicly disclose how much they have removed.
- For biomass carbon removal, one ethanol facility with carbon capture and storage (which is considered carbon removal since the CO_2 was initially captured from the air via photosynthesis), located in the U.S. state of Illinois, sequestered 0.44 $MtCO_2$ in 2021,[91] the latest year for which data are available (U.S. EPA 2023b). The 2021 number is assumed for 2022 in the absence of updated data. The only other facility of its kind permanently sequestering CO_2 became operational in July 2022 in North Dakota and captures and sequesters 0.18 $MtCO_2$/yr (EERC 2022).
- Other purchases that were delivered through voluntary markets added 0.044 $MtCO_2$ in 2022 via purchases of credits from DAC, mineralization, and biomass-based approaches (Höglund 2022).

FIGURE 63 | Historical progress toward 2030 and 2050 targets for technological carbon removal

☒ **Right Direction, Well Off Track** **S-Curve Possible**



Notes: $MtCO_2$/yr = million tonnes of carbon dioxide per year. See Jaeger et al. (2023) for more information on methods for selecting targets, indicators, and datasets, as well as our approach for assessing progress.

Sources: Historical data from U.S. EPA (2023b); Climeworks (2021); and Höglund (2022). Targets derived from IPCC (2022b); and Fuss et al. (2018).

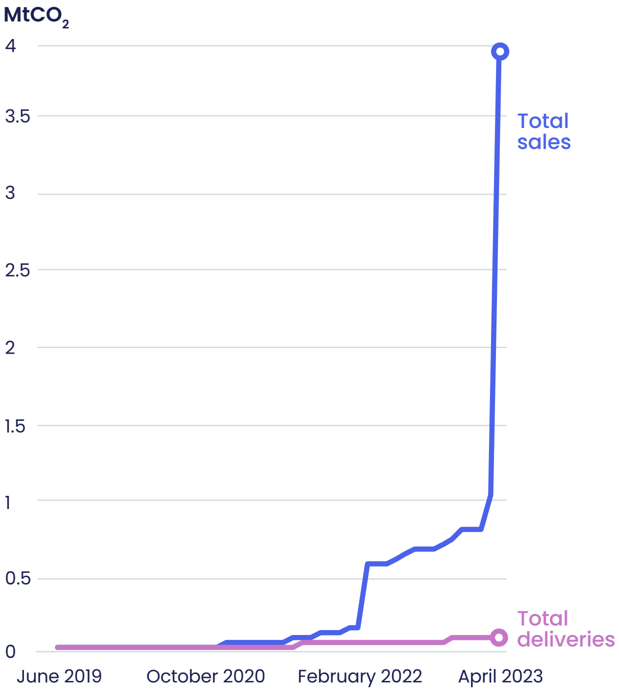
Data are incomplete and include only what is reported publicly. This comes to an estimated 0.57 $MtCO_2$ in 2022, and, although this total demonstrates a meaningful improvement from recent trends, it still amounts to less than 1 percent of the midpoint of the target amount of carbon removal needed by 2030 (Figure 63). The historical rate of change would need to accelerate more than 10-fold to meet the 2030 target. Reaching the lower bound target by 2030 would be equivalent to building more than 3 of the largest DAC plants in operation today (4,000 tCO_2/yr scale) every day until 2030. Reaching the upper bound would mean building 73 of this scale project every day.

If some of the current barriers to uptake of technological carbon removal are overcome, an S-curve growth trajectory is possible. Even though the number of tonnes removed today is small and all carbon removal technologies remain in the emergence phase—such that global progress made toward this near-term target is categorized as well off track—the momentum needed to drive change is rapidly accelerating in terms of commitments and investment.

Recent developments across technological carbon removal

In just the last five or so years, carbon removal technologies have transformed from a niche concept to a common component of climate action portfolios, supported by billions of dollars in public funding and hundreds of millions of dollars of private investment (Frontier 2023; U.S. Congress 2021). The total sales of technological carbon removal credits on the voluntary market have grown exponentially, providing some indication of where the sector as a whole is headed, and highlighting that many purchases in this new industry are being made in advance of project completion (Figure 64). The United States (Box 19) and several other countries have been early leaders here, and interest is beginning to broaden. According to the first *State of Carbon Dioxide Removal* report, launched in early 2023, peer-reviewed scientific literature on carbon removal now consists of nearly 30,000 English-language studies (Smith et al. 2023).

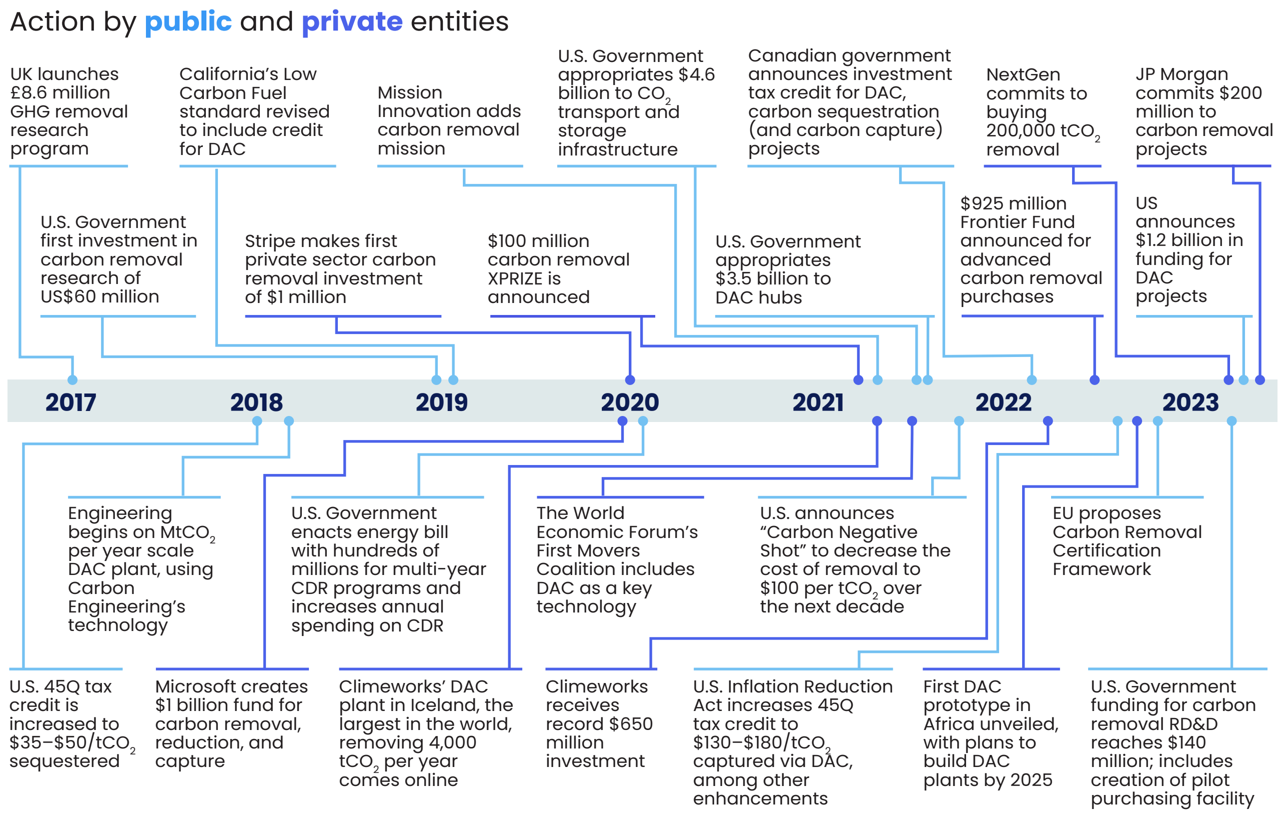
FIGURE 64 | **Total sales and deliveries of carbon removal credits**



Note: $MtCO_2$ = million tonnes of carbon dioxide. Includes purchases of tonnes removed by direct air capture, mineralization, electrochemical ocean carbon dioxide removal (CDR), biomass-based CDR (biochar, bio-oil injection), and macroalgae cultivation.
Source: Höglund and Niparko (2023).

Each of the past several years has seen a flurry of announcements, investments, supportive policies, and new CDR companies launching (Figure 65). For example, in the space of a year, two trade associations for carbon removal companies were launched—the Carbon Business Council in mid-2022 and the Carbon Removal Alliance in February 2023. Both aim to advance policies to support the plethora of fast-growing CDR companies in delivering carbon removal (Carbon Business Council 2022; Pontecorvo 2023). And in late 2022, the European Commission launched its proposal for a Carbon Removal Certification Framework (CRCF), the first public sector voluntary certification framework for high-quality carbon removal. Development of the CRCF is just the first step in this process; by late 2023 or early 2024 it will be discussed in the European Parliament and then transformed into legislation and certification methodologies tailored to each type of carbon removal. The aim of this framework is to improve the credibility of CDR projects and help drive scale-up accordingly.[92]

FIGURE 65 | Selected recent actions supporting development and deployment of carbon removal technologies



Action by **public** and **private** entities

UK launches £8.6 million GHG removal research program

California's Low Carbon Fuel standard revised to include credit for DAC

Mission Innovation adds carbon removal mission

U.S. Government appropriates \$4.6 billion to CO_2 transport and storage infrastructure

Canadian government announces investment tax credit for DAC, carbon sequestration (and carbon capture) projects

NextGen commits to buying 200,000 tCO_2 removal

JP Morgan commits \$200 million to carbon removal projects

U.S. Government first investment in carbon removal research of US\$60 million

Stripe makes first private sector carbon removal investment of \$1 million

\$100 million carbon removal XPRIZE is announced

U.S. Government appropriates \$3.5 billion to DAC hubs

\$925 million Frontier Fund announced for advanced carbon removal purchases

US announces \$1.2 billion in funding for DAC projects

Engineering begins on $MtCO_2$ per year scale DAC plant, using Carbon Engineering's technology

U.S. Government enacts energy bill with hundreds of millions for multi-year CDR programs and increases annual spending on CDR

The World Economic Forum's First Movers Coalition includes DAC as a key technology

U.S. announces "Carbon Negative Shot" to decrease the cost of removal to \$100 per tCO_2 over the next decade

EU proposes Carbon Removal Certification Framework

U.S. 45Q tax credit is increased to \$35–\$50/tCO_2 sequestered

Microsoft creates \$1 billion fund for carbon removal, reduction, and capture

Climeworks' DAC plant in Iceland, the largest in the world, removing 4,000 tCO_2 per year comes online

Climeworks receives record \$650 million investment

U.S. Inflation Reduction Act increases 45Q tax credit to \$130–\$180/tCO_2 captured via DAC, among other enhancements

First DAC prototype in Africa unveiled, with plans to build DAC plants by 2025

U.S. Government funding for carbon removal RD&D reaches \$140 million; includes creation of pilot purchasing facility

Notes: CDR = carbon dioxide removal; CO_2 = carbon dioxide; DAC = direct air capture; EU = European Union; GHG = greenhouse gas; $MtCO_2$ = million tonnes of carbon dioxide; RD&D = research, development, and demonstration; tCO_2 = tonnes of carbon dioxide; UK = United Kingdom; US = United States. This figure shows selected highlights of actions and activities the authors identified to be most important in the carbon removal space.

Source: Authors.

BOX 19 | U.S. action on carbon removal

As the largest cumulative historical GHG emitter, the United States has a responsibility to lead carbon removal development and deployment to help clean up these emissions (Fyson et al. 2020). *The Long-Term Strategy of the United States* outlines the need for around half a billion tonnes of technological carbon removal in the United States by midcentury, along with deep decarbonization and carbon removal from nature-based approaches, like reforestation (U.S. Department of State 2021).

U.S. government and private sector interest and action has increased massively to help meet this strategy. Federal investment in research has grown from near zero before 2020 to more than $140 million in 2023 (U.S. Senate 2022a). Moreover, in 2021 a major infrastructure law provided $3.5 billion—the largest-ever influx of funding for carbon removal anywhere—to build four "DAC hubs" that can each capture and store or use 1 $MtCO_2$/yr, plus an additional $115 million for DAC technology competition prizes. In that same year, the Department of Energy announced a "Carbon Negative Shot" initiative to reduce the price of carbon removal to \$100/tCO_2 removed over the following decade for pathways that can reach gigatonne scale (U.S. DOE 2021). In 2022, the Inflation Reduction Act more than tripled the level of support for CO_2 removal with DAC, from \$50/tCO_2 to \$180/tCO_2 (U.S. Senate 2022b). As context, prices for carbon removal per tonne of CO_2 vary widely today, with purchasers of carbon removal tonnes paying on the order of \$100/tCO_2 for some carbon mineralization approaches to more than \$2,000/tCO_2 for some DAC purchases (Höglund 2022).

Procurement of carbon removal is also gaining interest. The 2023 appropriations bill directed the Department of Energy to develop a pilot procurement program. And legislative proposals have also been introduced through larger-scale procurement of an increasing number of tonnes of carbon removal at declining prices at the federal level (the Federal CDR Leadership Act and the CREST Act) and in the states of California and Massachusetts (U.S. House of Representatives 2022; U.S. Senate 2022c; Commonwealth of Massachusetts 2023). The state of California has also introduced a bill that would require companies to purchase carbon removal to compensate for an increasing percentage of their remaining emissions through 2045, when the state has a net-zero greenhouse gas emissions target (State of California 2023a). These policies could all help create demand and greater certainty for suppliers of carbon removal.

As momentum around carbon removal in the United States grows rapidly, the private sector is also demonstrating increased interest in scaling up carbon removal technologies. Companies like Stripe, Microsoft, and Shopify have invested hundreds of millions of dollars in early purchases of carbon removal tonnes and have made efforts to make their processes transparent to provide learning for others (Stripe 2021; Microsoft 2021). In mid-2022, a coalition of companies, including Stripe and Shopify, launched Frontier, a commitment to purchase $925 million in permanent carbon removal between 2022 and 2030 (Frontier 2023). This commitment helps provide the demand signal for carbon removal companies to make investments to increase their supply.

Notes: DAC = direct air capture; GHG = greenhouse gas; tCO_2 = tonnes of carbon dioxide.

At the same time, there is some concern and skepticism about the growing momentum behind technological carbon removal. Some highlight the risk that carbon removal can distract from the needed focus on and investment in GHG emissions reductions today (Grant et al. 2021; Markusson et al. 2018; Temple 2021), while others criticize the lack of actual removals accounted for to date (Temple 2021). Some groups have also expressed concern that while these projects provide the dispersed, public benefit of cleaning up carbon pollution, they also have local impacts (e.g., land, energy, and water usage) that must be better understood and assessed on a project-by-project basis.

Regulations and governance structures will need to be created and strengthened to ensure that the industry is scaled in an equitable—and sustainable—manner (Mace et al. 2021; Lebling et al. 2023). Improving existing governance frameworks could include a range of public and private sector interventions at many levels (e.g., international, national, state, project), which could help to increase public acceptance and support for the technologies.

At the governmental scale, for example, national governments can include requirements for community engagement and consideration of environmental and social impacts of carbon removal projects as prerequisites for project developers to receive federal funding (Allen et al. 2022; Lebling et al. 2022a). National or state governments can also set legal minimum limits on the level of emissions reductions in meeting national or state climate goals (e.g., 80–90 percent emissions reductions with 10–20 percent of the original emissions counterbalanced by carbon removal) to help avoid reliance on carbon removal in place of emissions reductions, a concern known as mitigation deterrence. More clearly defining what counts as "hard-to-abate" and eligible to be counterbalanced by carbon removal would help justify these definitions (Lebling et al. 2023). Simultaneously, national and subnational governments can ensure that existing zoning and infrastructure planning regulations are sufficient to regulate new carbon removal infrastructure and that they do not concentrate any locally unwanted land uses near marginalized communities (Lebling et al. 2022a).

Within the private sector, governance structures can also be established to aid uptake. Private sector purchasers of carbon removal, and platforms that certify and sell carbon removal credits for voluntary markets, for instance, can include sustainability, community engagement, and other relevant stipulations for credits to be bought or sold as high-quality options. Project developers can also use community benefit agreements (binding contracts between developers of large-scale projects and communities that represent residents' interests) or other legal instruments to ensure that communities receive desired benefits like local employment opportunities or other types of community investment (Fraser 2022). Third parties that approve private sector climate commitments can provide guidance on relative levels of emissions reduction and carbon removal when meeting climate goals.

For example, the UN high-level expert group on the net-zero emissions commitments of nonstate entities has recommended that a net-zero target be based on a pathway to net zero grounded in a robust method consistent with limiting warming to 1.5°C, with emissions falling as close to zero as possible and residual emissions balanced by permanent removals, verified by a credible and independent third party. The group has also recommended that regulators develop regulations and standards for net-zero targets to ensure their credibility and prevent greenwashing (UN HLEG 2022).

There are also roles for international organizations and civil society organizations to play in improving governance of technological carbon removal. For instance, international organizations can strengthen existing data and inventory systems, ensure that accounting rules are robust, and create incentives for and engage with the carbon removal research community (Mace et al. 2021). Simultaneously, civil society organizations can use their platforms and resources to hold government and private sector actors to account, advocate for marginalized communities, and emphasize the importance of transparency in decision-making processes. Ultimately, governments, the private sector, and civil society will all need to work together to strengthen these governance frameworks as the industry continues to grow.

SECTION 9

Finance

Finance is a vital enabler of climate action, but current investment patterns are hindering the speed and scale of the transition to zero-carbon economies. Transforming power, buildings, industry, transport, forests and land, and food and agriculture, as well as scaling up carbon removal technologies, will all require significant increases in climate finance, as well as a broader transformation of the financial system (IPCC 2022b). Continued investment in fossil fuels, commodities that drive deforestation, and other high-emissions activities at current levels will put the Paris Agreement's 1.5°C temperature limit out of reach. Therefore, at the same time as scaling up climate investment, it is essential to phase out investments in high-emissions activities. Doing one without the other will be insufficient to meet climate goals; the level of investment in the zero-carbon economy needs to be many times greater than the level of investment in fossil fuels and other high-emissions activities (IEA 2023m). The decisions public and private actors make about what they invest in will determine how fast the transition to a net-zero world takes place.

Global assessment of progress for finance

Transforming the global financial system to support ambitious climate action entails both scaling up climate finance and aligning all finance with the Paris Agreement's goals. Scaling up climate finance includes

TABLE 9 | Summary of global progress toward finance targets

INDICATOR	MOST RECENT DATA POINT (YEAR)	2030 TARGET	2035 TARGET	2050 TARGET	LIKELIHOOD OF FOLLOWING AN S-CURVE	ACCELERATION FACTOR	STATUS
Global total climate finance (trillion US$/yr)[a]	0.85 (2021)	5.2	N/A	5.1	↗	8x	✖
Global public climate finance (trillion $/yr)[b]	0.332 (2020)	1.31–2.61	N/A	1.29–2.57	↗	8x	✖
Global private climate finance (trillion $/yr)[b]	0.333 (2020)	2.61–3.92	N/A	2.57–3.86	↗	>10x	✖
Ratio of investment in low-carbon to fossil fuel energy supply	1:1 (2023)	7:1	10:1 (2040)	10:1	↗	>10x	✖
Share of global GHG emissions under mandatory corporate climate risk disclosure (%)[c]	20 (2022)	75	N/A	100	↗	1.5x	!
Weighted average carbon price in jurisdictions with emissions pricing systems (2015$/$tCO_2e$)	23 (2023)	170–290	N/A	430–990	↗	>10x	✖
Total public financing for fossil fuels (billion $/yr)	1,100 (2021)[d]	0	0	0	↗	N/A; U-turn needed	↩

Notes: GHG = greenhouse gas; tCO_2e = tonne of carbon dioxide equivalent; yr = year. See Jaeger et al. (2023) for more information on methods for selecting targets, indicators, and datasets, as well as our approach for assessing progress.

[a] This indicator includes public and private, as well as domestic and international, flows.

[b] These indicators include domestic and international flows.

[c] Jurisdictions included in 2022 are Brazil, Egypt, India, Japan, New Zealand, Singapore, Switzerland, the United Kingdom, and the European Union. Disclosure requirements are not uniform among countries and apply to different or select types of firms (e.g., financial institutions or publicly traded firms) with diverse implementation timelines. We consider jurisdictions that implemented any form of mandatory requirement during the year it was approved, even if it enters into force in phases with different timelines. This approach can result in an overestimation as implementation timelines are enforced over the years in different stages.

[d] Data are a compilation of production and consumption subsidies, G20 state-owned entity fossil fuel capital expenditure, and international public fossil fuel finance from multilateral development banks and G20 countries' development finance institutions and export credit agencies.

Sources: Historical data from Naran et al. (2022); IEA (2023m); TCFD (2022); Wu and Uddin (2022); Naik (2021); Climate Watch (2023); World Bank (2023a); OECD and IISD (2023); Laan et al. (2023); and OCI (2023). Targets from IPCC (2018, 2022b); IEA (2021b); OECD (2017); UNEP (2021b, 2021f); Lubis et al. (2022); Climate Analytics and World Resources Institute (2021); G7 (2016); G20 (2009); and UNFCCC (2022a).

ramping up funding in all countries, from both public and private actors. Aligning finance with the Paris Agreement includes ensuring that a much higher ratio of investment goes to low-carbon energy compared to fossil fuels; measuring, reporting, and managing climate risks; accounting for the full climate costs of GHG emissions through carbon pricing mechanisms; and ending public financing for fossil fuels. While recent rates of change across all but one of these shifts are heading in the right direction, they remain well below the pace required (Table 9).

Scale up climate finance

A significant increase in climate investment will be needed to successfully limit global temperature rise to 1.5°C. While estimates vary, many converge around $4 trillion to $5 trillion per year globally between 2030 and 2050 to invest in transforming energy, transport, agriculture, and land use to be net zero (OECD 2017; IEA 2021b; Naran et al. 2022; IPCC 2022b). This figure, $5 trillion per year, amounts to around 5 percent of global GDP (Naran et al. 2022), and both public and private climate finance will need to increase to meet these goals.

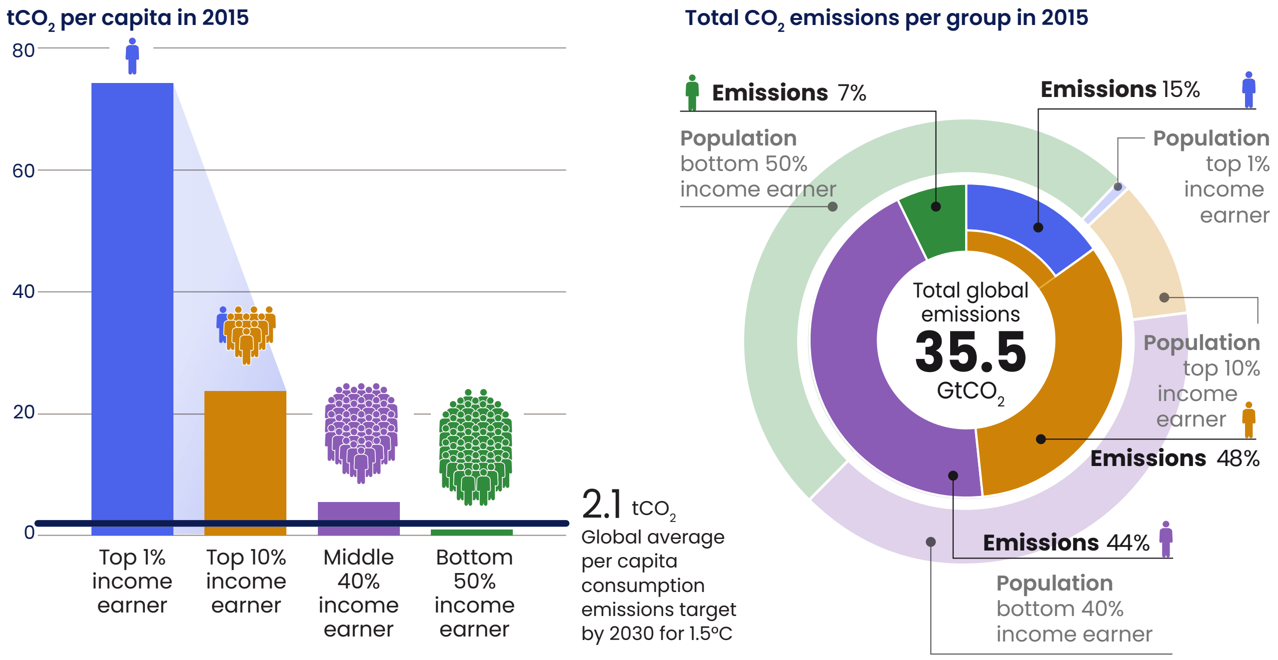
Scaling up public finance, both domestic and international, is vital to ensuring a rapid transition to net-zero and resilient societies. This is especially true for areas where the private sector is not well suited to meeting objectives at the speed and scale necessary. This includes funding public services and infrastructure (e.g., transportation and energy networks); research, development, and deployment of new technologies; job training; and ecosystem protection and restoration. Public finance also plays a pivotal role in supporting, creating, and shaping markets, including through public procurement, as well as in catalyzing private investment in new technologies and regions (OECD et al. 2018). Lastly, public finance is important for ensuring equitable outcomes and a just transition. It can help ensure access to finance for individuals and governments who may not otherwise be able to raise resources for climate action. Politicians, especially in richer countries, frequently claim that insufficient public funds are available (Chemnick 2022). Yet the last few years have shown clearly that government spending by major economies in the trillions of dollars is possible to address other crises. G20 governments mobilized $14 trillion in fiscal spending in 2020–21 to deal with the COVID pandemic (Nahm et al. 2022). Government military spending has exceeded $2.2 trillion per year since 2019 (Liang et al. 2023a). It is clear, therefore, that public spending at the scale of trillions of dollars is economically possible. It is just not yet happening for climate.

It is also vital to scale up climate finance from the private sector. As set out above, private finance is not a substitute for public investment, but the vast amount of capital under private control can and should be put to work in enabling the net-zero transformation. Governments have a large, well-tested, and effective toolkit for shifting private investments. This includes traditional sectoral environmental regulations that can force companies to invest in cleaner technologies, as well as finance-specific policies, such as financial regulation, fiscal, and monetary policy (Whitley et al. 2018). Much of the discussion around mobilizing private climate investment has focused on “de-risking” incentives in the form of subsidies to private actors. These proverbial “carrots” can play an important role, especially when directed at getting finance to flow to underserved countries, communities, and promising new technologies. Alongside this, governments can use “sticks,” including regulation and taxation, to provide markets with policy certainty that the transition to net-zero economies is inevitable and irreversible, and to direct private finance where it is needed to enable this transition (Gabor 2021).

Any discussion of finance must also consider issues of equity and justice (Robins 2020). Both greenhouse gas emissions and climate resilience are closely connected to wealth. The poorest countries and communities have done little to cause the climate crisis but are most vulnerable to its impacts (see Figure 66). This is a double injustice. The increased costs of dealing with impacts of climate change reduces the resources the poorest have to invest in mitigation. Providing adequate financing for the poorest and most vulnerable communities, and making sure they have a say in how finance is used, is therefore imperative for ensuring an equitable and just transition. These equity principles apply both between and within countries.

Looking at equity between countries, lower-income states face greater barriers to climate investment than rich nations. In lower-income countries, smaller tax bases limit their fiscal policy, lack of foreign exchange reserves limit their monetary policy, and the higher cost of capital limits their ability to borrow from international capital markets. They therefore need international

FIGURE 66 | Per capita and absolute CO_2 consumption emissions by four global income groups in 2015



Notes: CO_2 = carbon dioxide; $GtCO_2$ = gigatonnes of carbon dioxide; tCO_2 = tonnes of carbon dioxide. Per capita CO_2 consumption emissions, and absolute CO_2 consumption emissions by four global income groups in 2015, compared with emissions-reduction targets for 2030 for limiting warming to 1.5°C. Income thresholds in 2015 are according to US$ purchasing power parity in 2011: 1 percent > $109,000; 10 percent > $38,000; middle 40 percent > $6,000; poorest 50 percent < $6,000.

Source: UNEP (2020b).

support to enable them to equitably transition to net-zero economies at the speed and scale required to reach global net zero by midcentury. In the past couple of years, various assessments have attempted to break down how much of the external financing support developing countries need. The IPCC estimates developing countries would need $1.4 trillion to $2.8 trillion per year up until 2030 just to finance investments in mitigation, compared to developed countries, which need $0.9 trillion to $1.7 trillion per year (IPCC 2022b). The Independent High-Level Expert Group on Climate Finance, convened by the Egyptian Presidency of COP27, the UK Presidency of COP26, and the United Nations Climate Change High-Level Champions for COP26 and COP27, estimated that investment needs for climate action (both adaptation and mitigation) in developing countries, excluding China, would be between $2 trillion to $2.8 trillion per year by 2030, and that $1 trillion of this would need to come from external sources (Songwe et al. 2022).

Given this, governments agreed a core principle of the UN climate convention that governs the international response to the climate crisis of "common but differentiated responsibilities and respective capabilities." This recognizes that while all countries have a responsibility to address climate change, some countries have a larger responsibility due to greater GHG emissions and more capability to invest in climate action. Furthermore, richer countries should help support decarbonization and adaptation in the poorest countries, which have historically emitted less, are hit first and worst by climate change, and have the least capacity to recover from crises. To this end, developed countries have taken on obligations under the UNFCCC and the Paris Agreement to provide climate finance for developing countries (UNFCCC 1992, 2015), but they have not yet fulfilled their commitments.

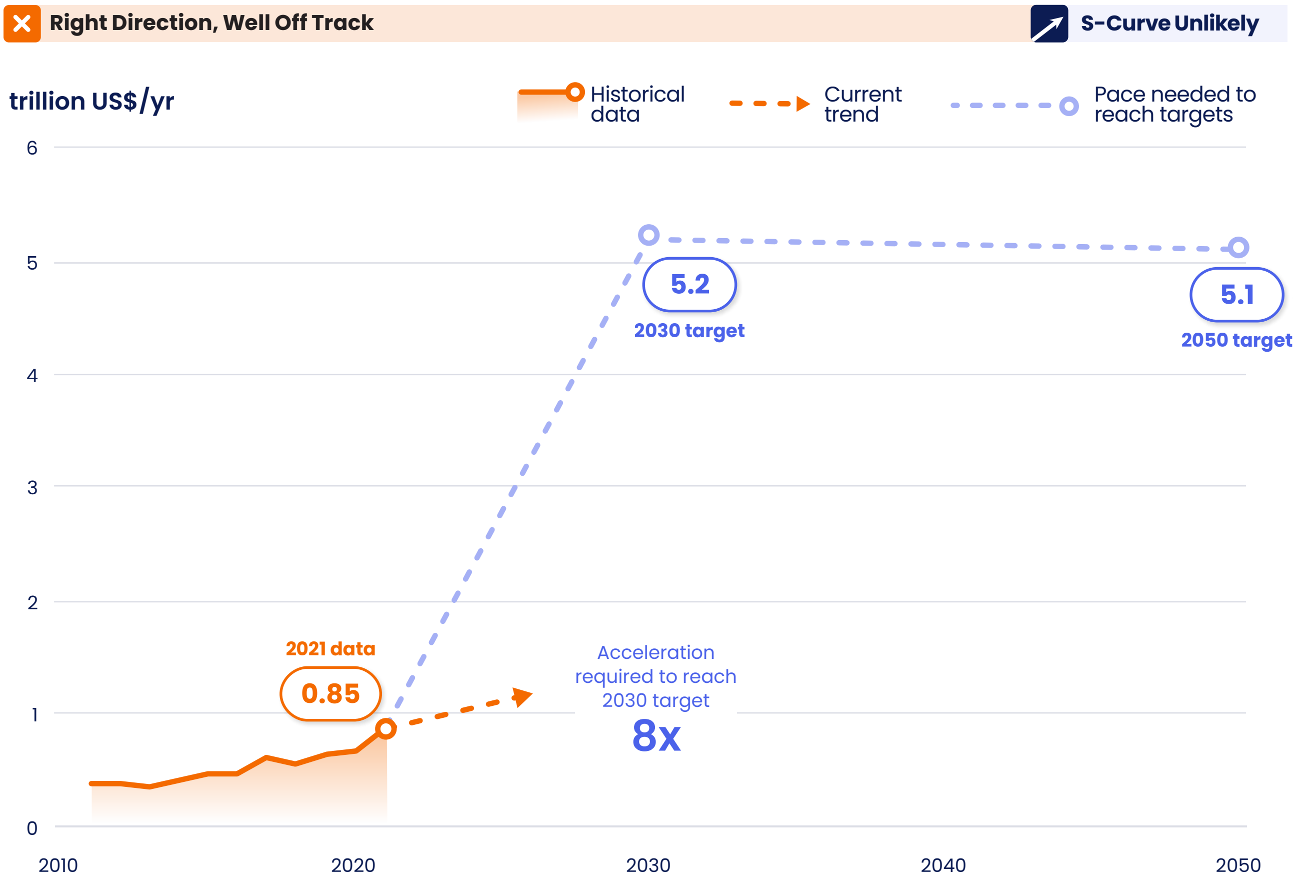
Regarding equity within countries, equity principles suggest the effort of raising public finance should be shared fairly, with the richest individuals and companies contributing more in tax revenues, and the benefits of climate investments directed toward those most in need. This is a matter not merely of morality but also of effectiveness: a large-scale survey of 40,000 respondents in 20 countries found that climate policies financed through progressive taxation and with progressive use of revenues garner greater support (Dechezleprêtre et al. 2022). An example of progressive taxation is windfall taxes on record profits by fossil fuel companies, which have been implemented by the European Union and many individual European governments during the energy crisis (Reuters 2022). Several governments are also making increased efforts to ensure that the outcomes of public climate investments address the needs of communities that have historically borne the brunt of polluting activities, and workers in sectors that will be particularly affected by decarbonization. For example, the European Union's Just Transition Mechanism provides dedicated financial resources to regions with the least resources and facing the greatest challenges in phasing out high-emissions activities (WRI 2021), while the U.S. Justice40 Initiative sets a goal that 40 percent of the benefits from federal investments in climate and clean energy flow to disadvantaged communities (White House 2021). Private climate investments, at a minimum, should aim to avoid causing harm to communities and to redress any negative impacts that do occur. Ideally, these investments should also prioritize the needs of the poorest and most vulnerable communities and give them a say in where finance is directed and how it is used. Government regulation and oversight will be important to ensure that public and private climate investments respect human rights and environmental standards and that they are focused on delivering a just transition.

FINANCE INDICATOR 1:
Global total climate finance (trillion $/yr)

- **Targets**: Global climate finance flows (public and private, domestic and international) reach $5.2 trillion per year by 2030 and $5.1 trillion per year by 2050.

Quantitative measures of climate finance flows are difficult to capture and estimate given available data and definitional challenges.[93] Climate Policy Initiative (CPI) estimates that in the five years preceding 2021, climate finance increased by an average of $61.6 billion per year.[94] In 2021, CPI estimated that total global flows of climate finance, including public and private, domestic and international flows, reached $850 billion to $940 billion, an all-time high (Naran et al. 2022). By comparison, that same year, total global investment in fossil fuels was estimated at $915 billion (IEA 2023m). Climate finance jumped considerably between 2020 and 2021—by at

FIGURE 67 | Historical progress toward 2030 and 2050 targets for global total climate finance



Note: yr = year. This indicator includes public and private, as well as domestic and international, flows. See Jaeger et al. (2023) for more information on methods for selecting targets, indicators, and datasets, as well as our approach for assessing progress.

Sources: Historical data from Naran et al. (2022). Targets derived from IPCC (2018, 2022b); IEA (2021b); OECD (2017); and UNEP (2021b, 2021f).

least $185 billion, or 27 percent—a meaningful improvement relative to recent trends, but progress remains well off track. Global climate finance still needs to more than quintuple to reach the target of $5.2 trillion per year by 2030. This equates to an average increase of $490 billion per year—roughly eight times faster than recent increases (Figure 67). After this report went through peer review, Buchner et al. (2023) published new data that indicate significant increases in tracked total global climate finance. Flows reached $1.1 trillion in 2021 and $1.4 trillion in 2022. These increases were concentrated in China, the United States, Europe, Brazil, Japan, and India, as well as in the renewable energy and transport sectors. But even when considering these gains, substantial increases will be required by 2030.

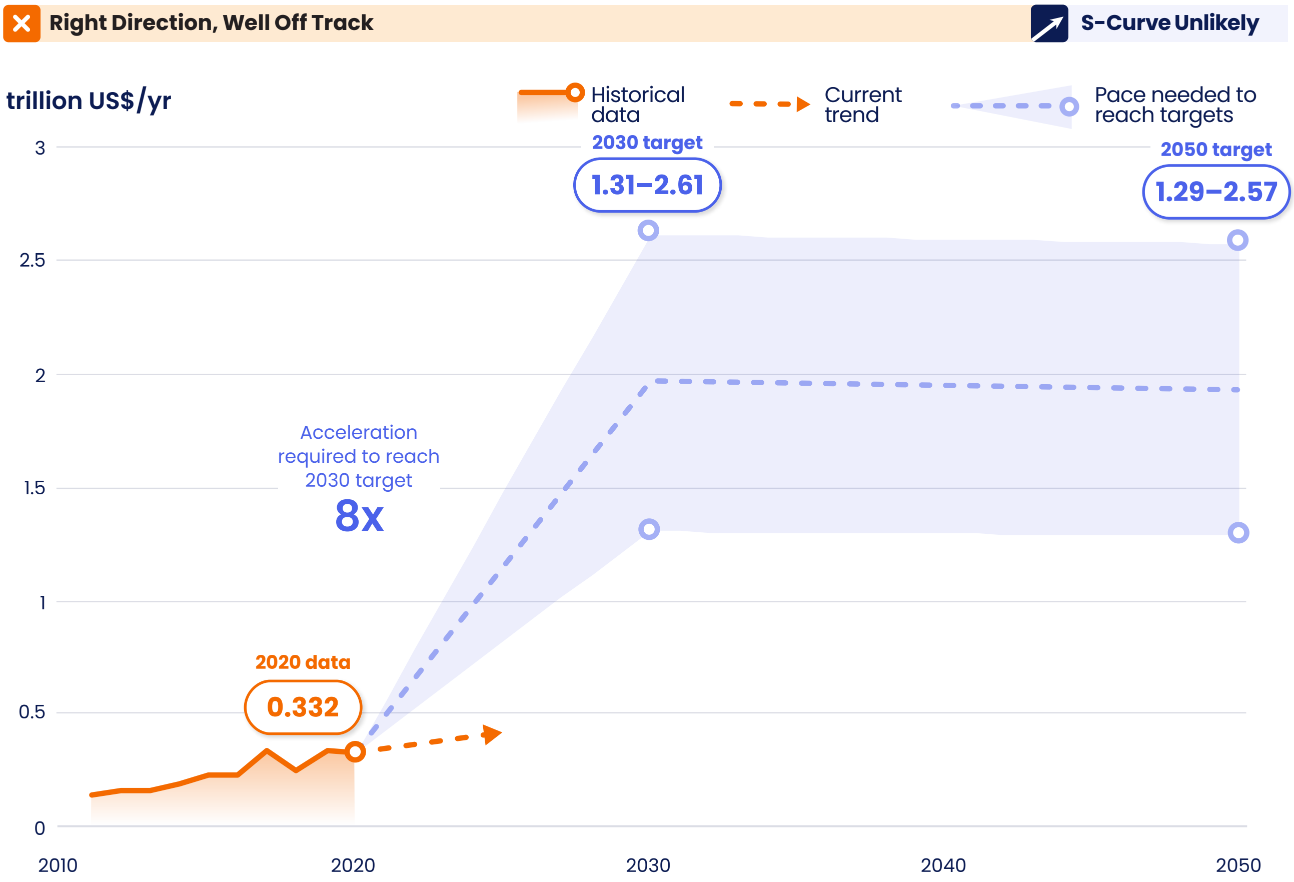
The need for significantly increased climate investment is particularly acute in developing countries. In 2020, total climate finance in non-OECD countries was just $392 billion, with around half of this in China alone (Naran et al. 2022; Choi et al. 2021). This is therefore less than a 10th of the at least $2 trillion per year in estimated climate investment needed in developing countries, excluding China, by 2030 (Songwe et al. 2022). Of climate finance in non-OECD countries in 2020, $171 billion (44 percent) was international climate finance flows, and nearly a fifth of these international flows, $31 billion, came from other non-OECD countries (Naran et al. 2022).

FINANCE INDICATOR 2:
Global public climate finance (trillion $/yr)

- **Targets:** Global public climate finance flows (domestic and international) reach $1.31 trillion to $2.61 trillion per year by 2030, and $1.29 trillion to $2.57 trillion per year by 2050.

Global public climate finance flows amounted to $332 billion in 2020, increasing by $19.2 billion per year, on average, between 2016 and 2020. However, public climate finance fell slightly in 2020 from an all-time high of $337 billion in 2019 (Naran et al. 2022)—a worsening relative to recent trends. Based on available data,[95] recent increases in public climate finance remain well off track—total funds would need to increase more than

FIGURE 68 | Historical progress toward 2030 and 2050 targets for global public climate finance



Note: yr = year. This indicator includes domestic and international flows. See Jaeger et al. (2023) for more information on methods for selecting targets, indicators, and datasets, as well as our approach for assessing progress.

Sources: Historical data from Naran et al. (2022). Targets derived from IPCC (2018, 2022b); IEA (2021b); OECD (2017); and UNEP (2021b, 2021f).

sixfold to reach the $2 trillion per year midpoint of the target range by 2030. This requires an average growth of $162 billion per year between 2020 and 2030—roughly eight times faster than recent increases (Figure 68). New data from Buchner et al. (2023), which were published after this report went through peer review, indicate significant increases in global public climate finance. Flows reached $549 billion in 2021 and $730 billion in 2022. But even with these gains, substantial increases will be required by 2030.

On average between 2019 and 2020, 73 percent ($233 billion) of global public climate finance was project financing (54 percent as market rate debt, 15 percent low-cost debt, and 4 percent equity), 15 percent ($48 billion) was balance sheet financing (11 percent as debt, 4 percent equity), and 11 percent ($35 billion) was grants. Development finance institutions (DFIs) provided the majority of public finance in 2019–20 (69 percent, $220 billion), with $120 billion coming from national DFIs, $65 billion from multilateral DFIs, and $35 billion from bilateral DFIs. During the same time period, an estimated 37 percent of public climate finance flowed internationally. Public finance was the largest source of international climate finance, accounting for 79 percent of total climate finance flowing across borders. The largest flows of public climate finance (from both domestic and international sources) in absolute terms were invested in East Asia and the Pacific ($180 billion). Proportionately, public climate finance is the most important source of finance in sub-Saharan Africa, making up nearly 90 percent ($17 billion) of the region's total (Buchner et al. 2021). Climate finance is not allocated equitably either among or within regions, with some countries receiving far greater sums than others (see Figure 69). In addition to scaling up overall finance, there is a need to address the inequity in where finance flows.

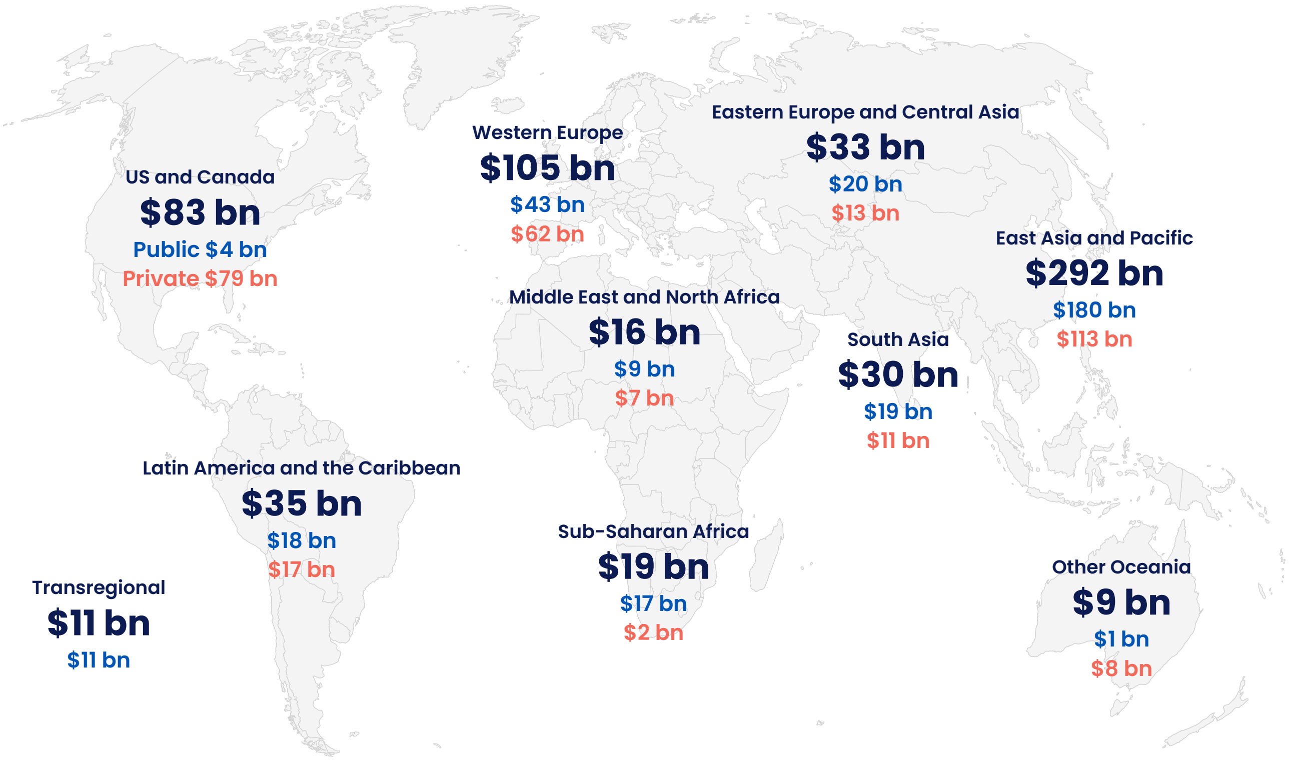
FINANCE INDICATOR 3:

Global private climate finance (trillion $/yr)

- **Targets**: Global private climate finance flows (domestic and international) reach $2.61 trillion to $3.92 trillion per year by 2030, and $2.57 trillion to $3.86 trillion per year by 2050.

Global private climate finance allocations from financial institutions, institutional investors, corporations, and households amounted to $333 billion in 2020,[96] a continuation of recent trends of an average $26.5 billion growth per year between 2016 and 2020 (Naran et al. 2022). Although heading in the right direction, current

FIGURE 69 | Destination region of climate finance, by public and private sources (billion U.S. dollars), 2019–20 annual average



Note: bn = billion; US = United States.
Source: Buchner et al. (2021).

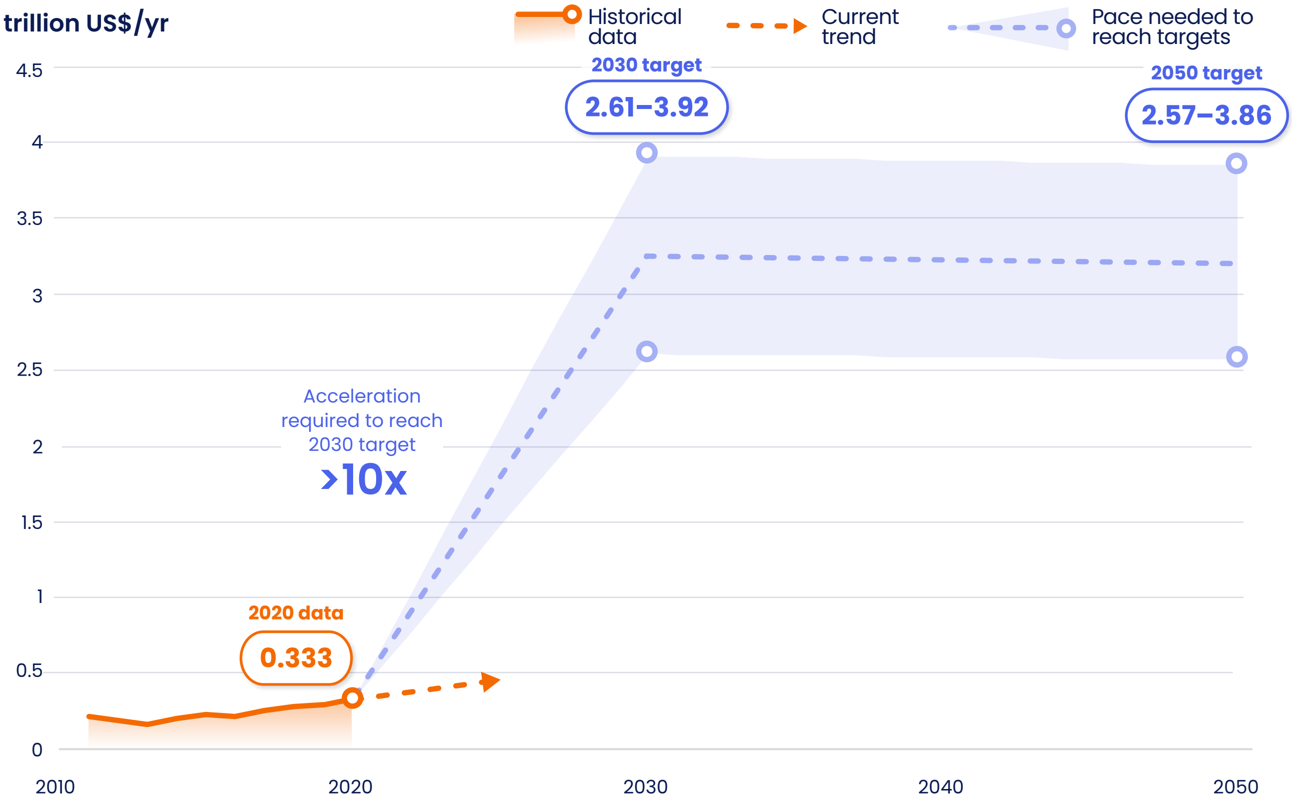
efforts remain well off track from the 2030 and 2050 targets. Total private climate finance will need to increase more than 10-fold by 2030 to reach $3.3 trillion per year (midpoint for the target range for 2030). This requires an average growth of $293 billion more each year between 2020 and 2030, over 10 times faster than historical growth rates (Figure 70). New data from Buchner et al. (2023), which were published after this report went through peer review, indicate significant increases in global private climate finance. Flows reached $565 billion in 2021 and $685 billion in 2022. But even with these gains, substantial increases will be required by 2030.

Corporations accounted for the largest share of private climate finance in 2019–20, with $124 billion invested. They were closely followed by commercial financial institutions, which financed $122 billion in 2019–20—up from $48 billion in 2017–18, representing the largest growth among private sources. On average between 2019 and 2020, 68 percent ($212 billion) of global private climate finance was balance sheet financing (46 percent as debt and 22 percent equity), and 31 percent ($97 billion) was project finance (19 percent as market-rate debt and 12 percent equity) (Buchner et al. 2021).

A large majority of climate finance in the United States and Canada (95 percent) and Oceania (88 percent) came from private sources (Figure 71). In Western Europe, private sources accounted for 60 percent. Conversely, in sub-Saharan Africa, private finance accounted for just 12 percent of the region's total climate finance (Buchner et al. 2021). Private climate finance in developing countries mobilized by developed countries' public interventions was $13.1 billion in 2020 (OECD 2022a),[97] accounting for just 3.9 percent of global private climate finance flows.

FIGURE 70 | Historical progress toward 2030 and 2050 targets for global private climate finance

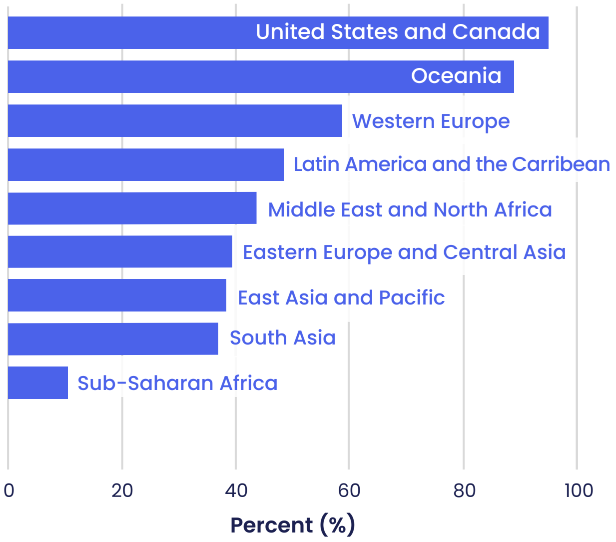
☒ **Right Direction, Well Off Track** **S-Curve Unlikely**



Notes: yr = year. This indicator includes domestic and international flows. See Jaeger et al. (2023) for more information on methods for selecting targets, indicators, and datasets, as well as our approach for assessing progress.

Sources: Historical data from Naran et al. (2022). Targets derived from IPCC (2018, 2022b); IEA (2021b); OECD (2017); and UNEP (2021b, 2021f).

FIGURE 71 | Share of climate finance originating from private sources, annual average 2019–20



Source: Buchner et al. (2021).

Align finance with the Paris Agreement

In addition to scaling up climate finance, there is also a need to curb financing of high-emissions activities that are incompatible with the Paris Agreement's goals. Increasing climate finance without simultaneously phasing out investments in high-emissions activities, such as fossil fuel extraction, will not reduce emissions rapidly enough to limit temperature rise to 1.5°C. Scaling up climate finance and phasing out investments in the fossil economy and other high-emissions activities are therefore two sides of the same coin.

There is some progress here: investment in clean energy now exceeds that of fossil fuels (IEA 2023m). This reflects not only the growing commitment of public and private institutions to finance the transition but also the accelerating economic attractiveness of the zero-carbon economy as technologies move along S-curves and outcompete the incumbent fossil economy. The clean energy economy has begun to replace the fossil economy, but it is not happening rapidly enough. Global investment in fossil fuels in 2023 is still projected to reach over $1 trillion (IEA 2023m). Not only is the phase-down of fossil fuel investments and retirement of fossil fueled assets necessary for reducing emissions, but some of the savings from doing so can be reallocated to increasing climate finance.

Catalyzing a faster financial transition requires reform of the global financial architecture to make it more equitable and responsive to climate and development needs (United Nations 2023). A variety of policies and regulations can also help curb financing for fossil fuels and other activities incompatible with a 1.5°C pathway, including better climate risk integration for market participants through climate disclosures, policies to price in the full cost of greenhouse gas emissions, and an end to subsidies and other public financing for fossil fuels.

Disclosure of climate-related risks can help align private sector financial flows with 1.5°C pathways by enabling corporations, investors, and regulators to correctly assess and manage those risks, factoring them into their capital allocation and transition plans. The growing awareness of climate-related risks in the private sector is already driving businesses to adopt net-zero transition plans and adapt their businesses. But mandatory disclosure requirements will be needed to standardize and measure risk across the entire economy. Regulators also need to ensure that risk integration does not lead to inequitable outcomes such as reducing financing to vulnerable communities affected by climate impacts.

Climate change has been called "the greatest and widest-ranging market failure ever seen" (Stern 2006), with economists arguing that market prices do not properly account for the damages that rising GHG emissions inflict on communities and ecosystems. Putting a sufficiently high price on carbon—through explicit carbon pricing or policy measures that impose an implicit price on emissions—can send a market signal that can help shift investment and consumption decisions so they contribute to reducing emissions to a level compatible with a 1.5°C pathway (IPCC 2018). Carbon pricing provided $95 billion in revenues in 2022 (World Bank 2023d), and wider adoption of carbon pricing has the potential to increase government revenues, which can be channeled into public climate finance.

Fossil fuels are the biggest source of greenhouse gas emissions driving the climate crisis. Phasing out fossil fuel subsidies and other public financing for fossil fuels not only reduces a direct source of funding but also provides a signal to private investors, who must also eventually phase out investment in fossil fuels. Government subsidies reduce the cost of fossil fuels below the market price, effectively acting as a negative carbon price, counteracting the effects of carbon pricing mechanisms. Many fossil fuel projects rely on government support to be economically viable—for example, in the United States, it is estimated that production subsidies bring nearly half of new, yet-to-be-developed oil investments into profitability (Erickson et al. 2017)—so even where public funding constitutes a small portion of total costs, removing this support can influence far greater amounts of private investment. The IPCC finds that removing fossil fuel subsidies could reduce global emissions between 1 percent and 10 percent by 2030 while improving public revenues (IPCC 2022b). Government investments in fossil fuels represent a significant opportunity cost, since such public funding could be directed to climate investments that could ensure energy access, reduce emissions, and help societies adapt to climate impacts. In addition, there is evidence that recent inflation is primarily driven by rising fuel costs, which raises the price of production and transportation of goods, heating and cooling, and transportation. Climate investments that help transition to clean energy and reduce demand for fuel can reduce inflationary pressure (Melodia and Karlsson 2022). While not covered here due to lack of comprehensive data, phasing out subsidies for other high-emissions activities, including deforestation, forest degradation, and other harmful land impacts and related commodities could also reduce emissions while promoting nature goals under the Kunming-Montreal Global Biodiversity Framework.

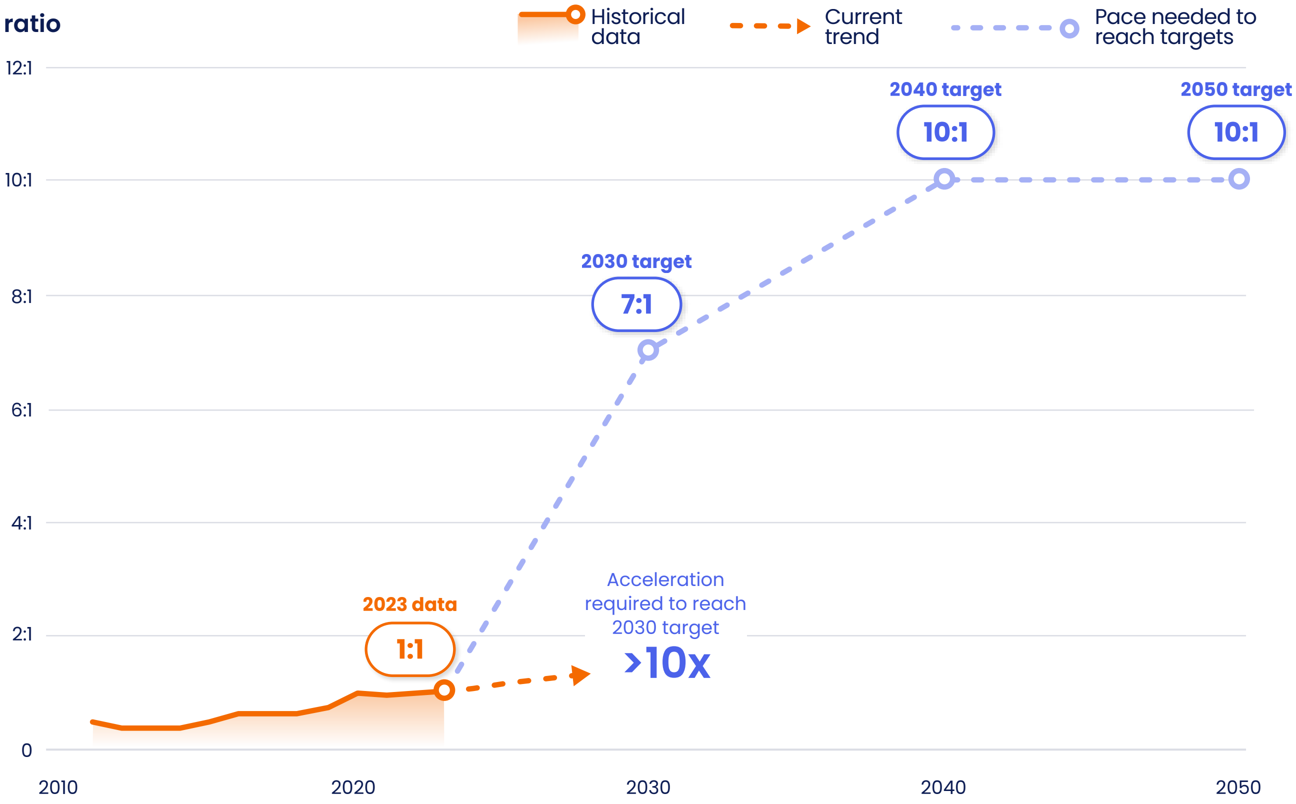
FINANCE INDICATOR 4:
Ratio of investment in low-carbon to fossil fuel energy supply

- **Targets:** The ratio of investments in low-carbon to fossil fuel energy supply increases to 7:1 by 2030 and to 10:1 by 2040, with this 10:1 ratio sustained through 2050.

Shifting all investment from fossil fuels to low-carbon energy supply is critical to holding global temperature rise to 1.5°C. Based on an analysis of IPCC, IEA, and Network for Greening the Financial System scenarios of long-term investment requirements for 1.5°C-aligned pathways, Bloomberg New Energy Finance (BNEF) derived target ratios for investment in low-carbon to fossil energy supply of 4:1 for 2021–30 (range 2:1 to 6:1), 6:1 for 2031–40 (range of 5:1 to 9:1), and 10:1 for 2041–50 (range of 6:1 to 16:1). For the 2030 target, we use the 7:1 ratio BNEF calculated based on a linear growth trajectory from the current ratio to meet the decadal average targets (Lubis et al. 2022).

FIGURE 72 | Historical progress toward 2030, 2040, and 2050 targets for ratio of investment in low-carbon to fossil fuel energy supply

☒ **Right Direction, Well Off Track** **S-Curve Unlikely**



Note: See Jaeger et al. (2023) for more information on methods for selecting targets, indicators, and datasets, as well as our approach for assessing progress.

Sources: Historical data from IEA (2023m); targets from Lubis et al. (2022).

This year, 2023, marked the first time ever that investments in low-carbon energy supply exceeded investments in fossil fuel energy supply:[98] $1.1 trillion to $1.05 trillion (IEA 2023m). Although investment in low-carbon energy supply has been rising in recent years, it is not rising fast enough, nor is fossil fuel investment declining rapidly enough to be consistent with holding temperature increase to 1.5°C. Based on current trends, the ratio of investment in low-carbon energy supply to fossil fuel supply, currently 1:1, would be only 1.5:1 by 2030, well off track from the 7:1 ratio needed for 2030 (Figure 72). In addition to scaling up investment in low-carbon energy supply, there is also a need to electrify end uses such as transportation and heating that currently require fossil fuels.

Given that these ratios are based on both the level of clean energy investment increasing and the level of fossil fuel investment decreasing, the state of play and drivers of change are similar to those set out for Finance Indicators 1, 2, 3, and 7, namely policies and measures to increase public climate finance and incentivize private investment in clean energy, and to reduce public support for fossil fuels. What this indicator captures that is not included in others is global total investment in fossil fuels, from private sources, in addition to public finance captured in Indicator 6.

FINANCE INDICATOR 5:
Share of global GHG emissions under mandatory corporate climate risk disclosure (%)

- **Targets:** Share of global greenhouse gas (GHG) emissions subject to mandatory disclosures of corporate climate risks aligned with the Task Force on Climate-Related Financial Disclosures (TCFD) recommendations reach 75 percent in 2030 and 100 percent in 2050.

Disclosure of climate-related risks can help corporations assess the risks and opportunities they face with the transition to a zero-carbon economy and decide where to target investments to adapt their businesses. It is one of the first steps they can take as they develop their net-zero targets and transition plans. Similarly, reliable, standardized, and comparable disclosures will also allow financial institutions and governments to deploy capital efficiently and monitor and manage risks at a portfolio and systemic level, complementing other tools to align the movement of capital with a 1.5°C pathway. Most climate risk disclosures have been based on the Task Force on Climate-Related Financial Disclosures framework, which has been widely adopted and become the standard framework for climate-related financial disclosures (TCFD 2022; Kröner and Newman 2021). However, disclosure on climate risks is still mostly done on a voluntary basis, with incomplete information and inconsistent quality that is not fully aligned with the TCFD's recommended disclosures. This hinders mobilization of sufficient capital on an aggregate level to drive the systemic transition needed (TCFD 2022; Bingler et al. 2022). The framework has also faced criticism for its narrow focus on financial risks and opportunities that concern financial returns without considering other stakeholders and nonfinancial impacts that may lead corporations to prioritize risk reduction instead of building resilience across most vulnerable communities and actively contributing to the climate transition. Governments can play a crucial role in mandating standardized and high-quality disclosures so there is universal coverage and uniformity in reporting as well as moving beyond the perspective of financial materiality.

Regulators in most of the world's largest economies and capital markets have been considering mandating such disclosures and incorporating them into the supervision of the corporate and financial sector. In 2022, the number of countries with mandatory climate-related disclosures grew to 35, including Brazil, Egypt, India, Japan, New Zealand, Singapore, Switzerland, the United Kingdom, and the European Union countries (TCFD 2022; Wu and Uddin 2022; Naik 2021).[99] They correspond to about 20 percent of global emissions, a meaningful improvement compared to recent trends and the previous year (about 3 percent in 2021) thanks to regulatory requirements in high-emitting nations such as India, Japan, and the EU countries.

A major reason for the increase in coverage was the approval of the European Union's Corporate Sustainability Reporting Directive (CSRD), which will require reporting on a wide range of sustainability disclosures, including climate-related risks, pollution, and the circular economy (European Parliament 2022). It will also expand the scope of reporting to about 50,000 entities, including more than 10,000 non-EU firms, thereby effectively extending its requirements beyond EU borders (Holger 2023).

Although it builds on the TCFD framework, the CSRD goes beyond it by incorporating the "double materiality" concept, where corporations have to disclose not only how the environment impacts them financially (i.e., single materiality) but also the material impacts of their businesses on the climate and society, including in nonfinancial aspects (Täger 2021). This approach aims to make corporate disclosures serve a wider goal of corporate responsibility to society at-large beyond the narrow financial perspective. As the International Sustainability Standards Board (ISSB) has ruled out the double materiality approach in its framework, it is up to regulatory bodies to include it in their mandatory requirements (de Arriba-Sellier 2023; Alexander and Ensign-Barstow 2022).

Despite the recent positive developments, efforts remain off track and progress will need to occur about 1.5 times faster to reach the three-quarters target for 2030. There is also a need to ensure that these disclosure policies include land-based emissions. If a few large-emitting countries follow the example of others in adopting mandatory disclosures, coverage of global emissions would experience rapid, nonlinear progress and rise dramatically (Figure 73). For example, China and the United States represent about 40 percent of global emissions combined (Climate Watch 2023), and both countries are contemplating mandatory disclosure rules, which would get coverage on track to the target. Additionally, if major country members of the International Organization of Securities Commissions follow the organization's endorsement of the ISSB and call for its adoption, then coverage would grow significantly and accelerate adoption across the rest of the world (IOSCO 2023).

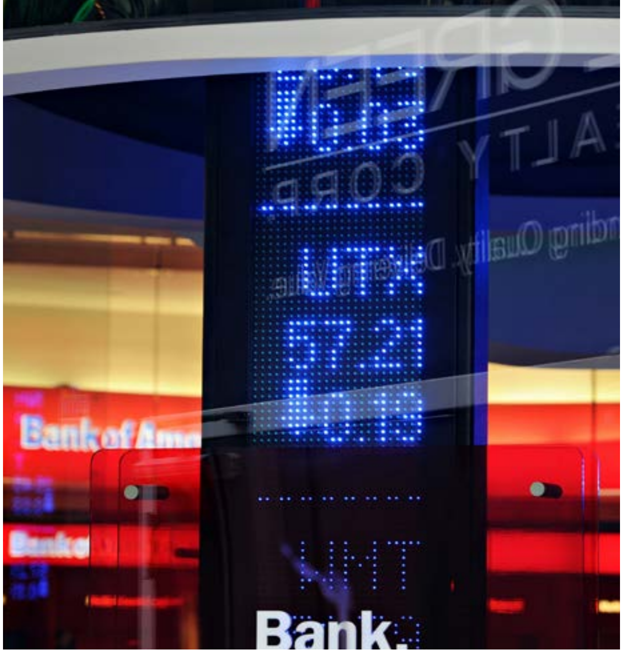


FIGURE 73 | Historical progress toward 2030 and 2050 targets for share of global GHG emissions under mandatory corporate climate risk disclosure

Notes: GHG = greenhouse gas. Jurisdictions included in 2022 are Brazil, Egypt, India, Japan, New Zealand, Singapore, Switzerland, the United Kingdom, and the European Union. Disclosure requirements are not uniform among countries and apply to different or select types of firms (e.g., financial institutions or publicly traded firms) with diverse implementation timelines. We consider jurisdictions that implemented any form of mandatory requirement during the year it was approved, even if it enters into force in phases with different timelines. This approach can result in an overestimation, as implementation timelines are enforced over the years in different stages. See Jaeger et al. (2023) for more information on methods for selecting targets, indicators, and datasets, as well as our approach for assessing progress.

Sources: Historical data from TCFD (2022); Wu and Uddin (2022); Naik (2021); Climate Watch (2023); and authors' calculations. Targets derived from Climate Analytics and World Resources Institute (2021).

FINANCE INDICATOR 6:

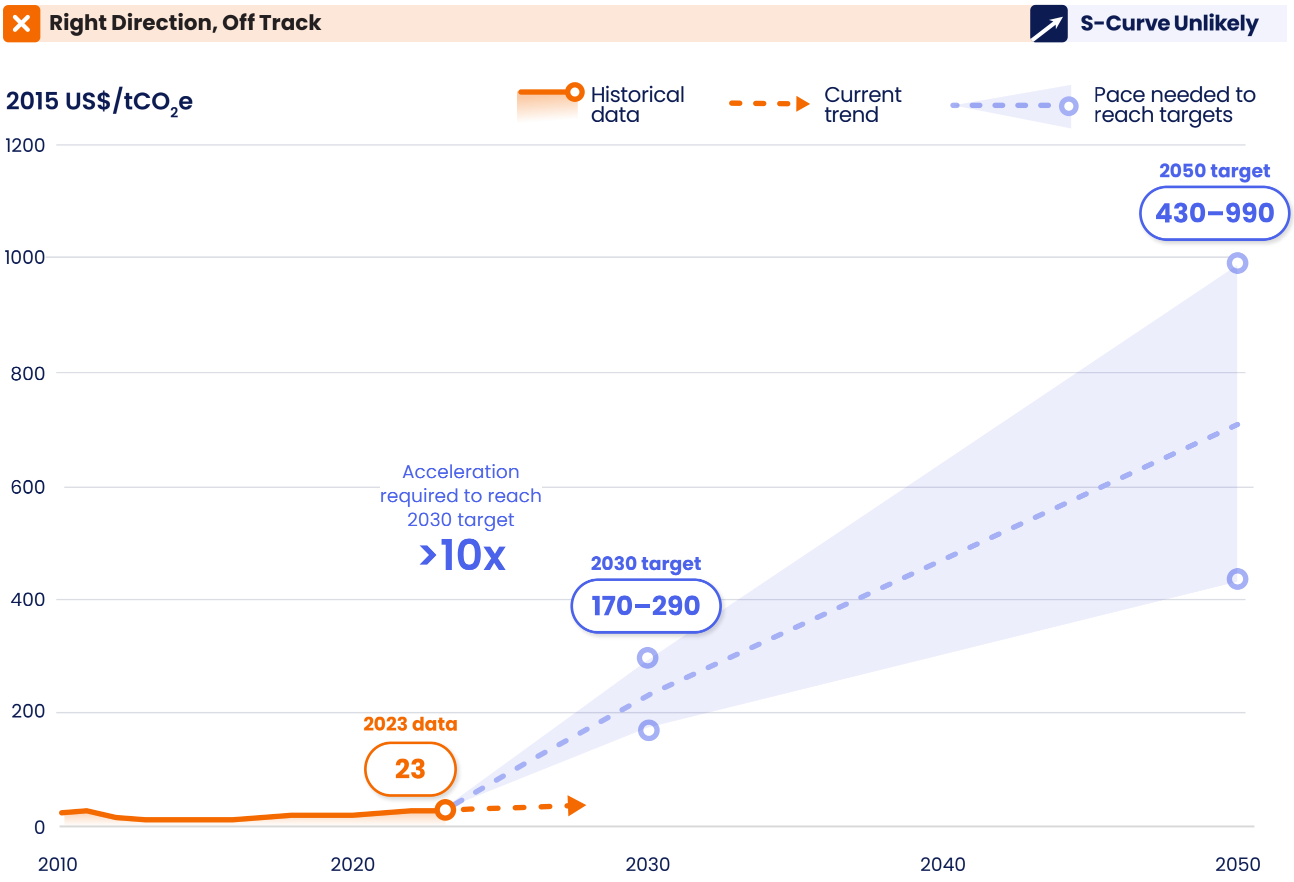
Weighted average carbon price in jurisdictions with emissions pricing systems (2015\$/tCO_2e)

- **Targets:** The weighted average carbon price in jurisdictions with pricing systems in place reaches \$170–\$290 per tonne of carbon dioxide equivalent (tCO_2e) in 2030 and \$430–\$990/tCO_2e in 2050.[100]

Well-designed carbon pricing systems could play a role in helping align economies with a 1.5°C trajectory. But in jurisdictions with carbon pricing systems in place, prices are insufficient—sometimes due to design issues such as overallocation of permits or inadequate coverage of high-emitting sectors—to fully account for the costs associated with rising GHG emissions or to send a strong enough signal to drive shifts in behavior and investments in line with 1.5°C. Less than 5 percent of global emissions have carbon pricing at or above the \$40–\$80/tCO_2e range that is estimated to be consistent with a 2°C pathway, and no areas are pricing carbon at the minimum end of the target range of \$170/tCO_2e required by 2030 to be consistent with a 1.5°C pathway (IPCC 2022b; World Bank 2023d). Most jurisdictions with pricing at or above the \$40–\$80/tCO_2e range are in Europe, joined by only Uruguay outside the continent. Only Uruguay, Liechtenstein, Switzerland, and Sweden currently have carbon pricing above \$100/tCO_2e. Uruguay is notable as the only developing country with carbon prices above \$40/tCO_2e (World Bank 2023a).

The average carbon price globally, weighted by share of emissions in territories covered by carbon pricing, was \$23.23/tCO_2e in 2023. Average carbon price increased by \$2.35 per year on average between 2019 and 2023 (World Bank 2023a), and at this rate of change, global average carbon prices will be \$39.69/tCO_2e in 2030, far short of the target range of \$170–290/tCO_2e. Global progress made in increasing carbon pricing and coverage therefore remains well off track, with the most recent year of data representing worsening relative to recent trends. Instead, the average price would need to increase by \$29.54 per year—more than 10 times the historical growth rate (see Figure 74). As of April 2023, 39

FIGURE 74 | Historical progress toward 2030 and 2050 targets for weighted average carbon price in jurisdictions with emissions pricing systems



Notes: 2015 \$/tCO_2e = 2015 dollars per tonne of carbon dioxide equivalent. See Jaeger et al. (2023) for more information on methods for selecting targets, indicators, and datasets, as well as our approach for assessing progress.

Sources: Historical data adapted from World Bank (2023a); targets from IPCC (2022b).

countries and 33 subnational jurisdictions have carbon pricing through a carbon tax or an emissions trading system (ETS).

There are equity concerns with carbon pricing, particularly that businesses will pass the costs on to consumers, making energy and transportation more expensive. Although the poorest emit the least, they may feel a greater burden from carbon pricing and subsidy removal, as they have the least ability to pay. Policies to redistribute the revenues raised by carbon pricing systems more equitably, such as rebates or earmarked spending on climate investments, can help increase acceptability and minimize regressive impacts (IPCC 2022b).

Where governments continue to provide fossil fuel subsidies, this counteracts the price signal provided by carbon pricing systems, reducing the effective carbon price; carbon pricing is most effective when paired with fossil fuel subsidy reforms (UNDP 2021).

FINANCE INDICATOR 7:

Total public financing for fossil fuels (billion $/yr)

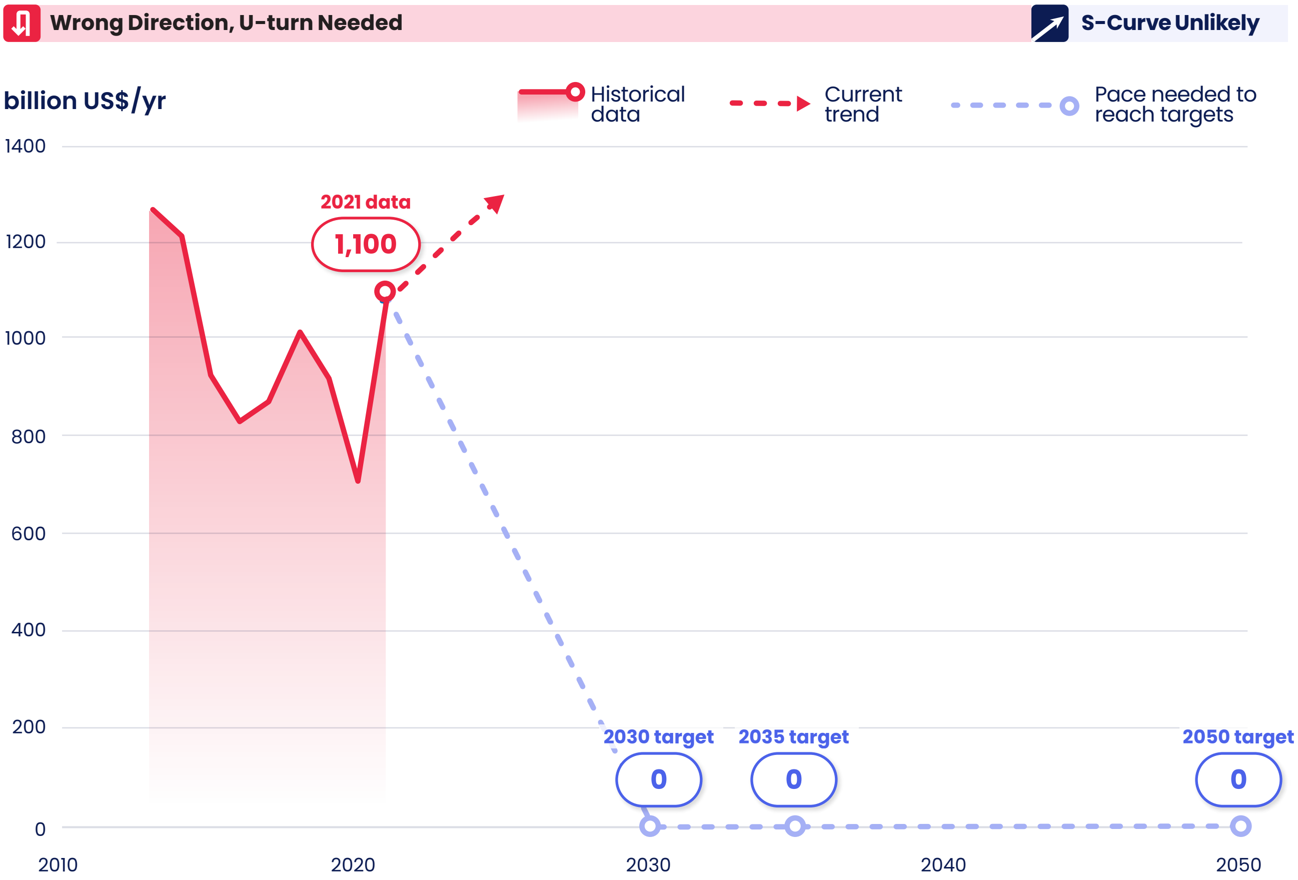
- **Targets:** Public financing for fossil fuels, including subsidies, is phased out by 2030, with Group of Seven (G7) countries and international financial institutions achieving this by 2025.

Total public financing for fossil fuels is estimated at over $1 trillion in 2021. Of this total, the majority, $732 billion, was production and consumption subsidies.[101] In 2021 these subsidies increased for the first time since 2018, nearly doubling from 2020 levels and reaching the highest level seen since 2014 (OECD and IISD 2023). Of this fossil fuel investment, $323 billion was by state-owned entities of G20 countries, an 8.5 percent increase from 2019 levels (Laan et al. 2023). An estimated $33 billion in international public financing for fossil fuel projects came from multilateral development banks (MDBs), G20 countries' export credit agencies, and development finance institutions (DFIs) (OCI 2023). Fossil fuel production and consumption subsidy data are only available for a reduced set of 82 economies in 2021, compared to 192 economies (i.e., near-global coverage) in 2020 and prior years (OECD and IISD 2023). The fact that subsidies nearly doubled, even with data available from fewer countries, highlights how progress has stopped and gone into reverse. The sharp increases in fossil fuel subsidies in 2021 alone have meant that global public financing for fossil fuels over the last five years has increased by an average of $5.3 billion per year—a concerning worsening relative to recent trends. It needs to decrease by an average of $85 billion per year between 2022 and 2030 to meet the 2030 phaseout target date. As a result, progress toward phasing out public financing

of fossil fuels globally by 2030 has changed from being well off track in 2020 to moving in the wrong direction in 2021 (Figure 75). Box 20 looks in more detail at progress in shifting international public finance for energy out of fossil fuels and into clean energy.

There are equity concerns that ending subsidies could hurt the poorest by increasing energy costs. Consumption subsidy reforms need to be well managed and address concerns about impacts on the poor. Studies across many countries have shown that the richest households capture most of the benefits of fossil fuel consumption subsidies and have therefore suggested that direct cash assistance to the poorest households would be a more effective way of ensuring energy access (Coady et al. 2017). Ending subsidies can also carry significant political implications, as they are sometimes used to shield domestic consumers from external price shocks. Drastic domestic energy price increases can lead to price instability that increases the likelihood of popular unrest and protests (McCulloch et al. 2022; Thöne et al. 2010). Modeling suggests that shifting production subsidies away from fossil fuels and toward renewable energy can stimulate greater job creation. An analysis of 12 studies around the world found that for every $1 million spent, 1.2 to 2.8 times as many full-time equivalent, near-term jobs could be created if invested in the renewable energy or energy efficiency sectors compared to the same level of investment in the fossil fuel sector (Jaeger et al. 2021).

FIGURE 75 | **Historical progress toward 2030, 2035, and 2050 targets for total public financing for fossil fuels**



Notes: yr = year. These data are a compilation of production and consumption subsidies, G20 state-owned entity fossil fuel capital expenditure, and international public fossil fuel finance from multilateral development banks and G20 countries' development finance institutions and export credit agencies. Production and consumption subsidies data were only available for 82 economies in 2021, compared to 192 economies in 2020 and prior years. See Jaeger et al. (2023) for more information on methods for selecting targets, indicators, and datasets, as well as our approach for assessing progress.

Sources: Historical data from OECD and IISD (2023); Laan et al. (2023); and OCI (2023). Targets derived from G7 (2016); G20 (2009); UNFCCC (2022a); IEA (2021b); and IPCC (2022b).

BOX 20 | Shifting international public energy finance away from fossil fuels and into clean energy

Today, 785 million people lack access to electricity, and 2.6 billion people do not have access to clean cooking (IEA 2021a). Sustainable Development Goal 7, "Ensure access to affordable, reliable, sustainable and modern energy for all" (UN General Assembly 2015), is currently not on track to be met. Fossil fuel–based approaches are failing to deliver energy access in a timely or cost-effective way, with the United Nations' Sustainable Energy for All concluding that "financing of fossil fuel projects as a means of closing the energy access gap should be terminated" (SEforAll and CPI 2020). To provide universal energy access and to reach net-zero emissions by 2050, developing countries need over $1 trillion per year in clean energy investment by 2030,[102] a sevenfold increase from the $150 billion average between 2015 and 2020 (IEA 2021a). Public finance can help catalyze clean energy investment, both by allocating significant sums of finance itself and by providing market signals for private investors, who often rely on public financing to make projects in developing countries viable.

At COP26 in Glasgow, 34 countries and 5 financial institutions pledged to end new public support for international unabated fossil fuel energy by the end of 2022 and to prioritize support for the clean energy transition (COP26 Presidency 2021). The commitment was designed with equity concerns in mind: rather than simply committing to end fossil fuel financing, which could leave countries without funding for energy access, the provision to shift fossil funding into clean energy, meaning the overall level of international public energy finance should at minimum be maintained if not increased.

The countries and institutions that signed the Glasgow pledge currently provide an estimated $19.5 billion per year in international public fossil fuel finance (McGibbon 2023). In May 2022, G7 climate, energy, and environment ministers adopted a near-identical commitment (G7 2022), which brings Japan, the only G7 member that had not signed the COP26 commitment, on board. Japanese international fossil fuel finance is estimated at a further $11 billion per year (Dufour et al. 2022).

As of the end of 2022, the deadline for meeting the Glasgow pledge, 8 of the 16 signatories with significant international public finance for energy had put policies in place that were publicly available and aligned with the Glasgow commitment (Canada, Denmark, the European Investment Bank, France, Finland, New Zealand, Sweden, and the United Kingdom). These policies are estimated to shift $5.7 billion per year out of fossil fuels and into clean energy. Overall data on international public energy finance has shown a concerted decline in fossil fuel financing, and after several years of parity, international clean energy finance is now the largest share (Figure B20.1).

Previously, actions to shift public financing from fossil fuels into clean energy were disjointed and did not receive the media attention that helps ensure accountability. Governments raised concerns that

BOX 20 | Shifting international public energy finance away from fossil fuels and into clean energy (continued)

unilateral action would put their businesses at a disadvantage compared to other countries that would continue subsidizing their fossil fuel industries, particularly through export credit agencies. The coordinated public nature of the Glasgow declaration has been key for getting action: governments felt more comfortable acting together, civil society has had a clear declaration to hold them accountable to, and the high-profile collective commitment sent a stronger market signal to private investors than governments acting alone.

Not all signatories to the Glasgow declaration have implemented their pledges. Four countries (Germany, Italy, Portugal, and the United States) have failed to publish policies on compliance with the Glasgow commitment. They may be shifting what they finance, but without clear policies it is difficult to tell or hold them accountable. Four countries have published policies falling short of the commitment (Belgium, the Netherlands, Spain, and Switzerland). If these countries were to fulfill the commitment, a further $13.7 billion per year would be shifted from fossil fuels to clean energy (McGibbon 2023). If all Glasgow pledge signatories uphold their commitment, it would close the gap to meeting the $100 billion per year climate finance goal, which stood at $17 billion as of 2020 (OECD 2022a).

FIGURE B20.1 | International public energy finance from MDBs and G20 countries' export credit agencies and development finance institutions

Note: G20 = Group of Twenty; MDB = multilateral development bank.
Source: OCI (2023).

Recent developments across finance

The last few years have seen a number of major developments in the global economy and politics that have had both positive and negative effects on the scale-up of climate finance flows and alignment of finance with climate goals. Recent developments relevant to both shifts are explored here, in turn.

Recent developments in scaling up climate finance

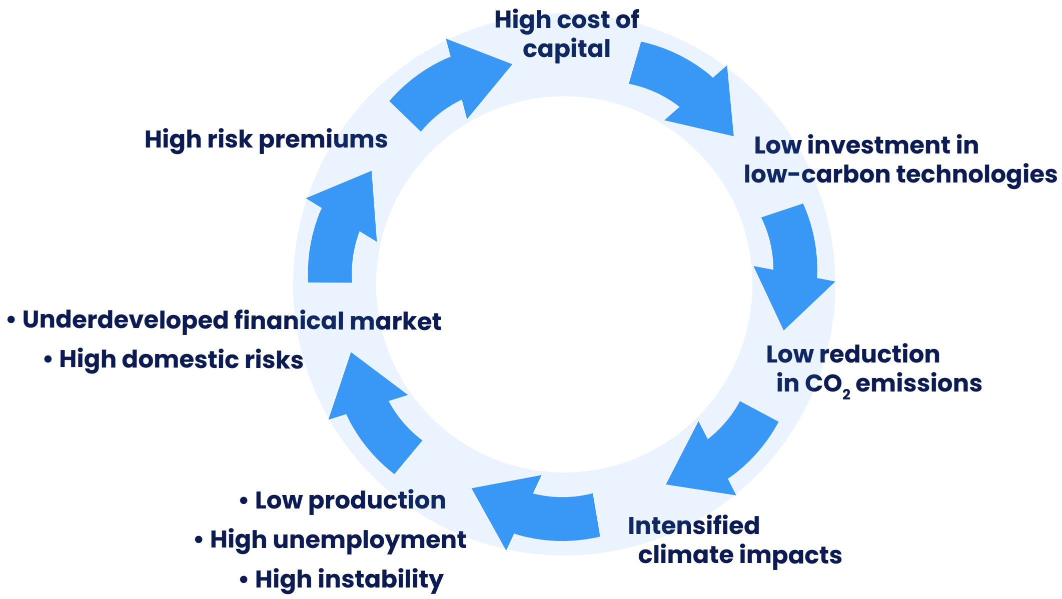
Recent developments in major economies have the potential to boost climate finance considerably. China has long led the world in investment in renewable energy (IEA 2023m), with annual public green financing estimated at RMB 1.1 trillion ($162 billion) in 2017–18 (Choi et al. 2021). The European Union has a target for 30 percent of its 2021–27 budget, an estimated €578 billion (around $633 billion) to go to climate (European Commission 2022a). In 2022, the United States showed signs of an effort to catch up after Congress passed the Inflation Reduction Act. While its headline spending level, as assessed by the Congressional Budget Office, is around $400 billion, many of the tax credits are uncapped, meaning overall spending could be much higher, with financial analysts at major banks estimating total federal spending could be double to triple this amount (Jiang et al. 2022; Goldman Sachs 2023). These investments have prompted the European Union to consider further public climate spending of its own, suggesting the potential for a race to the top among major powers in climate-focused industrial policy (Hensley and Lappetelainen 2023). Domestic climate investments by major economies can help drive down the cost of clean energy globally, as has been the case with solar and wind investments by Germany and China (Kavlak et al. 2018; Lacerda and Van Den Bergh 2014), helping spur emissions reductions beyond the country where investment takes place (Larsen et al. 2023).

However, the picture for developing countries is less positive. Squeezed by multiple recent crises including the ongoing effects of the pandemic, food and energy price spikes following the Russian invasion of Ukraine, broader inflation, and unsustainable debt burdens, many developing country governments lack the fiscal space to invest in climate (Songwe et al. 2022). The cost of capital for developing countries is higher, with some facing interest rates more than double those of developed countries, due to investors perceiving a higher risk of lending. This is a particular challenge for renewable energy development since it has higher upfront capital costs (but lower operating costs) compared to fossil fuel generation (Hirth and Steckel 2016). This leads to a "climate investment trap" (see Figure 76); the higher borrowing costs make it harder to develop economically viable projects, leaving countries unable to invest in transitioning their energy systems or in resilience. Being locked into the expensive and inefficient fossil fuel economy and left vulnerable to climate impacts leads to increased costs of disasters, higher unemployment, and greater political instability, which raises perceived risk and borrowing costs even further (Ameli et al. 2021). Over the past decade, increased climate vulnerability is estimated to have raised the average cost of sovereign debt for Climate Vulnerable Forum countries by 117 basis points, equivalent to $40 billion in additional interest payments on government debt (Buhr et al. 2018).

Unlocking greater levels of climate finance, including through reforming financial systems, can enable developing countries to invest in climate action at the scale needed, breaking out of the climate investment trap (Ameli et al. 2021). Supporting developing countries' ability to do this yields benefits not just for recipients but also for richer countries—first and foremost by helping accelerate action to address the climate crisis (action that brings global benefits), but also by boosting economies, developing export markets, shoring up supply chains, and addressing the root causes of political instability and conflict (Thwaites 2017).

Yet richer countries are not meeting even their modest commitments to provide and mobilize international climate finance. In 2009 at COP15 in Copenhagen, developed countries committed to mobilize $100 billion per year annually for developing countries by 2020, from a wide variety of sources, public and private, bilateral and multilateral (UNFCCC 2009). In 2015 at COP21 in Paris, governments agreed to extend this mobilization goal through 2025, and set a new collective quantified goal from a floor of $100 billion per year (UNFCCC 2015). The OECD estimated that total climate finance from developed to developing countries reached $83.3 billion in

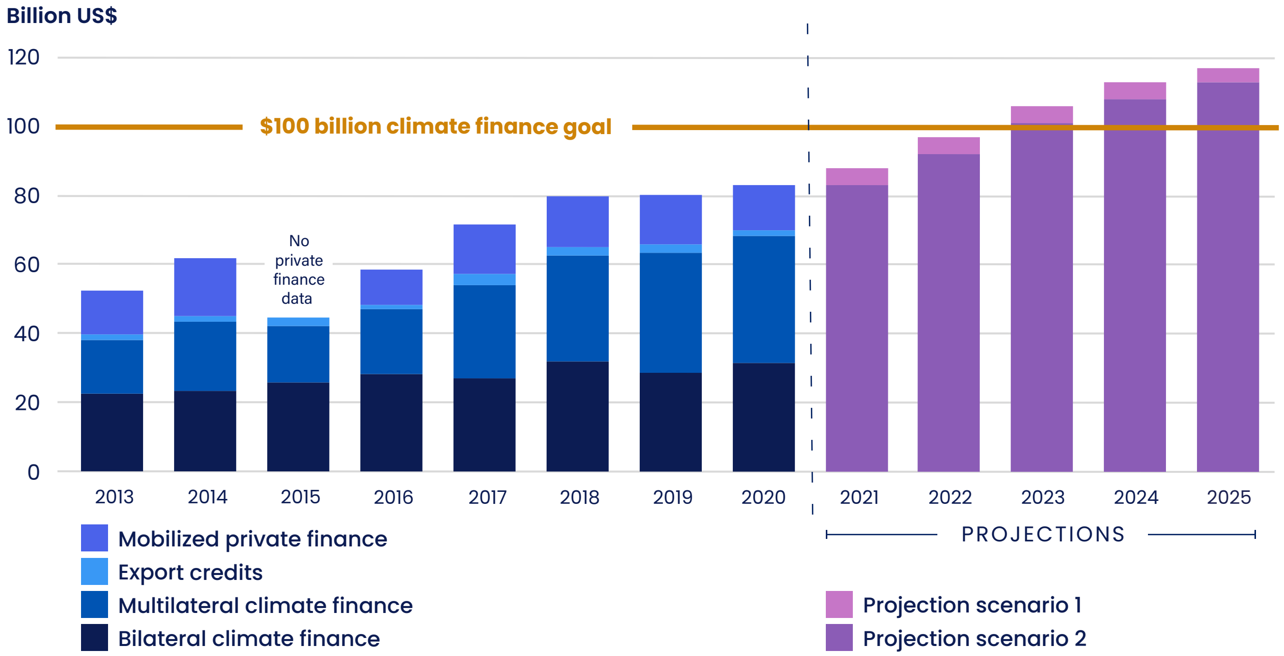
FIGURE 76 | The climate investment trap at the macroeconomic level



Note: CO_2 = carbon dioxide.
Source: Ameli et al. (2021).

2020 (OECD 2022a). Given this, a number of developing countries and civil society organizations have called for developed countries to ensure that their climate finance mobilization in subsequent years makes up for any shortfall in meeting the $100 billion commitment from 2020 onward, such that the total provision averages $100 billion per year between 2020 and 2025, which would be in the spirit of the Copenhagen and Paris commitments (V20 2021; Farand 2021). Developed-country governments project that they will deliver the $100 billion in 2023 (Figure 77), and that their climate finance mobilization for developing countries will average $100 billion per year over the period 2021–25 (Canada and Germany 2021). Doing so will require governments to continue to scale up their climate finance in line with their pledges. While the $100 billion was a collective goal by developed countries, not all countries have been making comparable efforts to meet it. The United States, for example, has by far the biggest shortfall, over $20 billion per year, between what it has provided in climate finance and assessments of its fair share of the effort based on objective indicators, such as size of economy, cumulative GHG emissions, and population (Bos and Thwaites 2021).

FIGURE 77 | Annual reported climate finance (2013–20) and projections (2021–25) toward the $100 billion goal



Note: Scenario 1 assumes that developed countries and international financial institutions fully deliver on their public climate finance commitments on time, and projects that private finance is mobilized at the same ratio to public dollars as was observed between 2016 and 2019. Scenario 2 is more conservative, assuming delays in meeting public climate finance commitments and a lower ratio of private finance mobilization than in 2016–19.

Sources: OECD (2022a, 2021a).

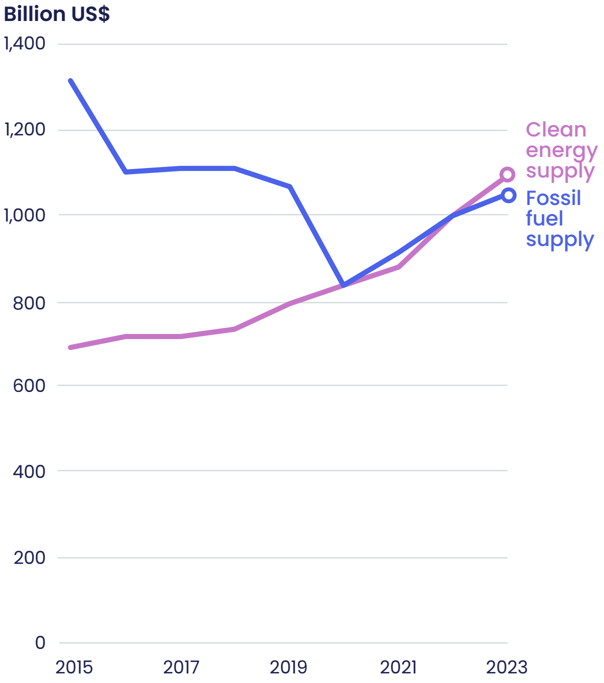
Recent developments in aligning finance with the Paris Agreement

While investment in clean energy has been rising steadily over the last decade, investment in fossil fuels had been on the decline up to and including 2020, but it has risen steadily since then, as countries recovered from the pandemic and the Russian invasion of Ukraine led countries to invest in increased oil and gas supply alongside continued efforts to build out clean energy (see Figure 78). The IEA projects investment in unabated fossil fuel supply is likely to rise by more than 6 percent in 2023, with current fossil fuel investments more than double the level in the IEA's Net Zero by 2050 scenario. Investment in clean energy supply is projected to rise by 9 percent in 2023, and clean energy will account for nearly 90 percent of all investment in electricity generation, yet, in a mirror image of fossil fuel overinvestment, this is still less than half of clean energy investment needed in the IEA's Net Zero 2050 scenario (IEA 2023m).

A major development in 2023 in climate risk disclosure was the launch of the International Sustainability Standards Board inaugural standards on sustainability and climate disclosures (IFRS 2023). These standards build upon the TCFD recommendations, with the requirement to disclose Scope 3 GHG emissions constituting an important improvement. The ISSB is expected to set the global baseline for corporate climate disclosures as major countries and international bodies such as the International Organization of Securities Commissions have endorsed it (Toplensky 2023; IOSCO 2023). Starting in 2024, it will also take over the monitoring responsibilities from the TCFD, which will be disbanded (FSB 2023). The ISSB climate standards are broadly aligned with the proposed U.S. rule of mandatory climate risk disclosures, which is expected to be finalized despite significant political opposition (Gensler 2022).

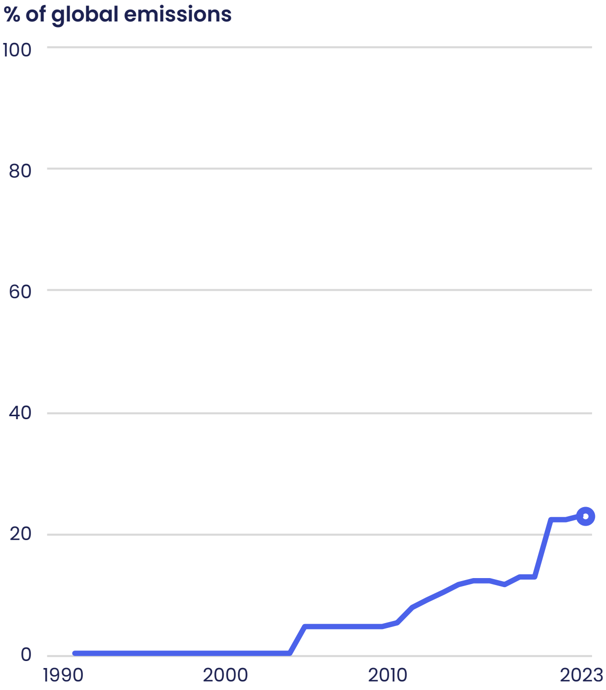
Only one new jurisdiction, Indonesia, has implemented a carbon pricing system since April 2022, with growth in carbon pricing coming through other jurisdictions expanding coverage or strengthening prices (World Bank 2023d). Carbon pricing systems covered 23 percent of global GHG emissions, less than a 1 percent increase in coverage from 2022 (Figure 79). Growth in the share of global emissions covered by carbon pricing has been largely stagnant since 2021, when China launched a national ETS that covers its power industry, bringing 4.5 $GtCO_2e$ (8.8 percent of global emissions) under a pricing regime (World Bank 2022a). While global carbon pricing coverage expanded due to progress in China, the average carbon price in the country remains around $8/$tCO_2e$, exerting a significant downward pressure on the global weighted average price. Nonetheless, China's new development represents an important step toward establishing a foundation to raise carbon prices over time.

FIGURE 78 | Global investment in clean energy and fossil fuel supply



Source: IEA (2023m).

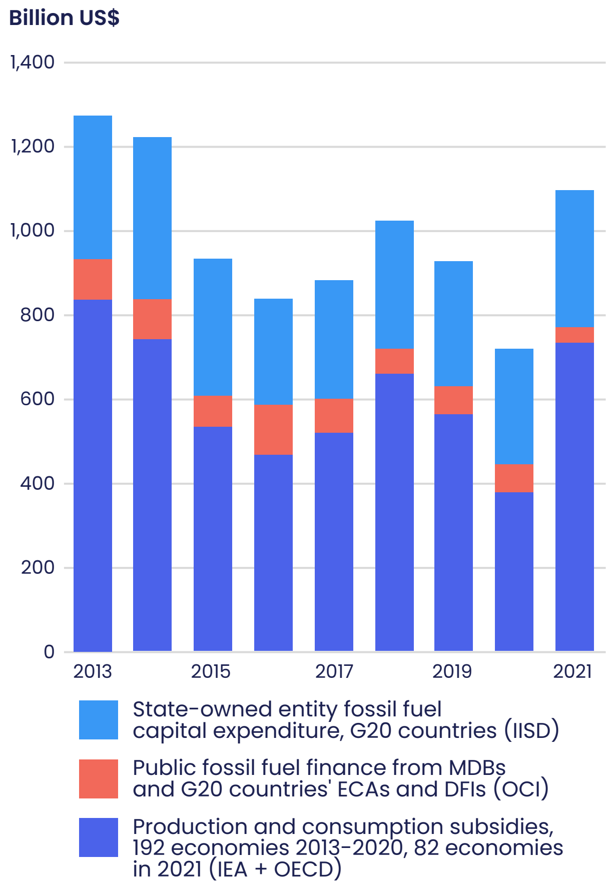
FIGURE 79 | Share of global emissions covered by a carbon price



Source: Historical data adapted from (World Bank 2023a).

Recent global events have resulted in wide swings in fossil fuel subsidy levels. The pandemic and subsequent oil price crash caused fossil fuel consumption subsidies to drop by 40 percent in 2020, but in 2021 they increased to exceed 2019 levels as economies rebounded from the pandemic and oil prices rose again (OECD 2022b). Production subsidies were already increasing before the pandemic, largely due to direct government spending by OECD countries on fossil fuel infrastructure and corporate debt relief (OECD 2021b). COVID-19 stimulus and recovery spending has exacerbated these trends, with multiple analyses finding that greater amounts of public funding are going to fossil fuels and other high-carbon sectors than to low-carbon development (UNEP 2021d). Just 5.3 percent of the $18.2 trillion in total COVID-19 fiscal spending in the 50 largest economies has been low-carbon, or 31.2 percent of $3.1 trillion in specific recovery spending (Oxford University Economic Recovery Project 2022). Between January 2020 and August 2022, the 38 largest economies and 8 multilateral development banks have committed $515 billion in new financing to fossil fuel–intensive sectors, compared to $488 billion to clean energy sectors (IISD 2022). Production subsidies rose in 2021 as governments sought to boost supply to meet rising demand as economies emerged from pandemic slowdowns (OECD 2022b).

FIGURE 80 | Breakdown of sources of public financing for fossil fuels

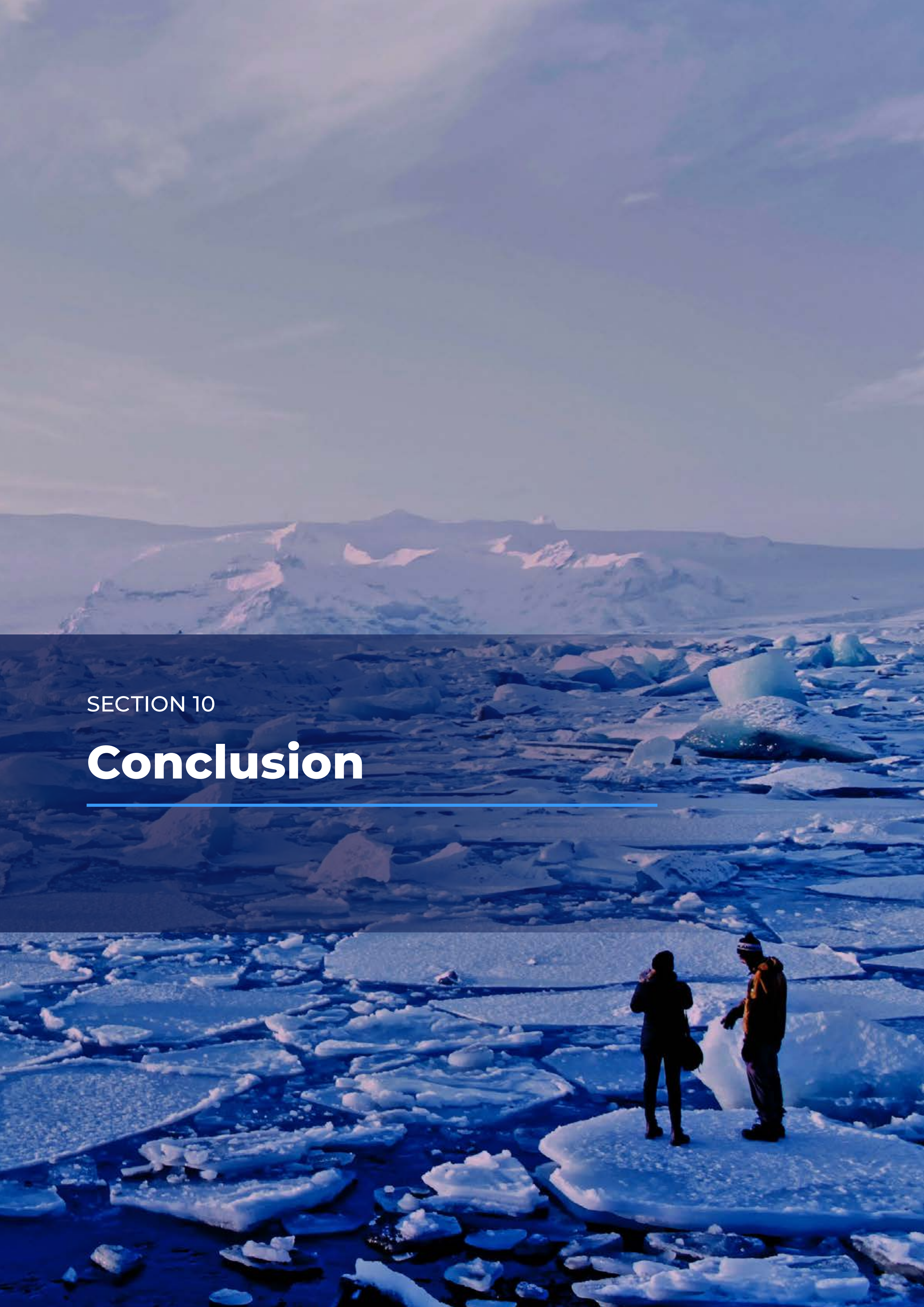


Notes: DFI = development finance institution; ECA = export credit agency; G20 = Group of Twenty; IEA = International Energy Agency; IISD = International Institute for Sustainable Development; MDB = multilateral development bank; OCI = Oil Change International; OECD = Organisation for Economic Co-operation and Development. These data are a compilation of production and consumption subsidies, G20 state-owned entity fossil fuel capital expenditure, and public fossil fuel finance from multilateral development banks and G20 countries' development finance institutions and export credit agencies. Production and consumption subsidies data were only available for 82 economies in 2021, compared to 192 economies in 2020 and prior years.

Sources: OECD and IISD (2021); Laan et. al (2023); OCI (2023).

Comprehensive production and consumption fossil fuel subsidy data are not yet available for 2022, but preliminary data from the IEA show that consumption subsidies rose above $1 trillion for the first time, almost double their already elevated 2021 levels, as the Russian invasion of Ukraine disrupted energy markets, causing prices to increase and governments to raise spending in an effort to protect consumers (IEA 2023c). Production subsidies are also expected to increase as governments seek alternative sources of supply to Russian oil and gas. This runs counter to commitments by the G7, G20, and all the world's governments at COP26 to phase out fossil fuel subsidies (G7 2016; G20 2009; UNFCCC 2022a). Data for 2022 for G20 state-owned entities (SOEs) show their capital expenditure on fossil fuels has remained at the same elevated postpandemic levels as 2021 ($322.6 billion, down from $323.2 billion). National oil companies of G20 countries have announced plans to use record 2022 profits to increase investments in upstream oil and gas in 2023 (Laan et al. 2023). This is at odds with the IEA's net-zero roadmap to achieve 1.5°C, which found that, beyond projects already committed to in 2021, no new investment in fossil fuel supply is required to meet global energy needs, a finding echoed by the IPCC's Sixth Assessment Report (IEA 2021b; IPCC 2022b).

Unlike domestic subsidies and SOE investment, international public financing for fossil fuels by MDBs and G20 countries' international financial institutions has shown a consistent declining trend, falling by nearly 60 percent in the past five years (OCI 2023). If the historical rate of decline in international public financing for fossil fuels between 2017 and 2021 continues, it could reach zero by the middle of the decade (Figure 80).



SECTION 10

Conclusion

The window to avoid increasingly devastating, oftentimes irreversible climate impacts is rapidly closing, with immediate and ambitious action now needed to limit warming to 1.5°C. To nearly halve GHG emissions by 2030 and reach net-zero CO_2 emissions by midcentury, transformational changes must accelerate across the world's highest-emitting sectors—power, buildings, industry, transport, forests and land, and food and agriculture. The rapid scale-up of carbon removal technologies and climate finance will also prove critical to combatting the climate crisis.

Recent years have witnessed many governments, companies, financial institutions, and civil society organizations shifting into gear to catalyze and deepen these transitions. But while recent rates of change are heading in the right direction toward most targets across these emission-intensive sectors, the world is on track to achieve just 1 of 42 targets—the share of electric vehicles in passenger car sales. Change is heading in the right direction at a promising but still insufficient speed for 6 indicators, and, for another 24 indicators, it remains well below the pace required to achieve near-term targets. Worse still, change for 6 indicators is heading in the wrong direction entirely. Data are insufficient to assess progress across the remaining 5 indicators with confidence (Figure 81).

Although the vast majority of indicators are not on track, notable progress has been made in some sectors. Solar buildup increased exponentially in 2022, power generation costs of solar photovoltaics and onshore wind and battery storage costs have declined rapidly in the past decade, and some experts are projecting that emissions from the power sector may have peaked in 2022. These examples show that rapid, nonlinear change is not only possible but already underway. Actions by governments—the U.S. Inflation Reduction Act, India's upcoming national carbon market scheme, Canada's Green Procurement policy, the European Union's Deforestation Regulation, and the Kunming-Montreal Global Biodiversity Framework, for example—also represent bright spots across the sectors that must transform. If successful, the upcoming Global Stocktake at COP28 can amplify this momentum and serve as a powerful springboard for greater climate action by, for example, informing economy-wide and sectoral targets communicated within the next round of NDCs and prompting governments to take much-needed steps toward phasing out unabated fossil fuels in electricity generation, halting deforestation and degradation, and shifting to zero-carbon transportation.

However, all sectors require further action to accelerate transformational change. In particular, a few indicators have shown a concerning slowdown of progress or worsening of trends, such as in the case of dramatically reducing deforestation, eliminating fossil fuel subsidies, and increasing public climate finance. For example, the level of global coal and gas use is still incompatible with a 1.5°C warming pathway and, in 2021, public financing for fossil fuels increased sharply, with government subsidies, specifically, nearly doubling from 2020 to reach the highest levels seen in almost a decade. Accelerating progress and reversing these worsening trends will require support from governments, the private sector, and civil society. In the year ahead, leaders across sectors will need to capitalize on the progress seen so far to work toward limiting warming to 1.5°C and ensuring that justice and equity are centered in all efforts toward this goal. While the path forward will require an enormous effort, the actions we take to get there can help us deliver developmental and societal benefits for all.

FIGURE 81 | Summary of progress toward 2030 targets

LIKELIHOOD OF FOLLOWING AN S-CURVE · ACCELERATION FACTOR[a]

∫	N/A	**S-curve Likely**
↗	5x	**S-curve Unlikely**
⇗	5x	**S-curve Possible**

✓ RIGHT DIRECTION, ON TRACK

∫	N/A[b]	Share of electric vehicles in light-duty vehicle sales (%)

! RIGHT DIRECTION, OFF TRACK

∫	N/A[b]	Share of zero-carbon sources in electricity generation (%)
∫	N/A[b]	Share of electric vehicles in the light-duty vehicle fleet (%)
∫	N/A[b]	Share of electric vehicles in two- and three-wheeler sales (%)
↗	1.5x	Reforestation (total Mha)
↗	1.2x	Ruminant meat productivity (kg/ha)
↗	1.5x	Share of global GHG emissions under mandatory corporate climate risk disclosure (%)

✕ RIGHT DIRECTION, WELL OFF TRACK

⇗	7x	Share of coal in electricity generation (%)
⇗	>10x	Share of unabated fossil gas in electricity generation (%)
⇗	9x	Carbon intensity of electricity generation (gCO_2/kWh)
↗	3x	Energy intensity of building operations (kWh/m^2)
⇗	4x	Carbon intensity of building operations (kgCO_2/m^2)
⇗	4x	Share of electricity in the industry sector's final energy demand (%)
⇗	>10x	Carbon intensity of global cement production (kgCO_2/t cement)
∫	N/A[b]	Green hydrogen production (Mt)
↗	6x	Number of kilometers of rapid transit per 1 million inhabitants (km/1M inhabitants)
↗	>10x	Number of kilometers of high-quality bike lanes per 1,000 inhabitants (km/1,000 inhabitants)
∫	N/A[b]	Share of battery electric vehicles and fuel cell electric vehicles in medium- and heavy-duty commercial vehicle sales (%)
∫	N/A[b]	Share of sustainable aviation fuels in global aviation fuel supply (%)
∫	N/A[b]	Share of zero-emissions fuels in maritime shipping fuel supply (%)
↗	4x	Deforestation (Mha/yr)

✕ RIGHT DIRECTION, WELL OFF TRACK

↗	>10x	Mangrove restoration (total ha)
↗	3x	GHG emissions intensity of agricultural production (gCO_2e/1,000 kcal)
↗	>10x	Crop yields (t/ha)
↗	8x	Ruminant meat consumption (kcal/capita/day)
⇗	>10x	Technological carbon removal (MtCO_2/yr)
↗	8x	Global total climate finance (trillion US$/yr)
↗	8x	Global public climate finance (trillion $/yr)
↗	>10x	Global private climate finance (trillion $/yr)
↗	>10x	Ratio of investment in low-carbon to fossil fuel energy supply
↗	>10x	Weighted average carbon price in jurisdictions with emissions pricing systems (2015$/$\text{tCO}_2\text{e}$)

WRONG DIRECTION, U-TURN NEEDED

⇗	U-turn needed	Carbon intensity of global steel production (kgCO_2/t crude steel)
↗	U-turn needed	Share of kilometers traveled by passenger cars (% of passenger-km)
∫	U-turn needed	Share of battery electric vehicles and fuel cell electric vehicles in bus sales (%)
↗	U-turn needed	Mangrove loss (ha/yr)
↗	U-turn needed	Share of food production lost (%)
↗	U-turn needed	Total public financing for fossil fuels (billion $/yr)

? INSUFFICIENT DATA

↗	Ins. data	Retrofitting rate of buildings (%/yr)
⇗	Ins. data	Share of new buildings that are zero-carbon in operation (%)
↗	Ins. data	Peatland degradation (Mha/yr)
↗	Ins. data	Peatland restoration (total Mha)
↗	Ins. data	Food waste (kg/capita)

FIGURE 81 | Summary of progress towards 2030 targets (continued)

Notes: gCO_2/kWh = grams of carbon dioxide per kilowatt-hour; $gCO_2e/1{,}000$ kcal = grams of carbon dioxide equivalent per 1,000 kilocalories; GHG= greenhouse gas; ha/yr = hectares per year; kcal/capita/day = kilocalories per capita per day; kg/capita = kilograms per capita; $kgCO_2/m2$ = kilogram of carbon dioxide per square meter; $kgCO_2/t$ = kilograms of carbon dioxide per tonne; kg/ha = kilograms per hectare; km/1M inhabitants = kilometers per 1 million inhabitants; km/1,000 inhabitants = kilometers per 1,000 inhabitants; kWh/m^2 = kilowatt-hour per square meter; Mha/yr = million hectares per year; Mt = million tonnes; $MtCO_2/yr$ = million tonnes of carbon dioxide per year; passenger-km = passenger-kilometers; tCO_2e = tonne of carbon dioxide equivalent; t/ha = tonnes per hectare; yr = year. For more information on indicators' definitions, deviations from our methodology to assess progress, and data limitations, see corresponding indicator figures in each section.

[a] For acceleration factors between 1 and 2, we round to the 10th place (e.g., 1.2 times); for acceleration factors between 2 and 3, we round to the nearest half number (e.g., 2.5 times); for acceleration factors between 3 and 10, we round to the nearest whole number (e.g., 7 times); and acceleration factors higher than 10, we note as >10. See data underlying these calculations in Appendix A.

[b] For indicators categorized as S-curve likely, acceleration factors calculated using a linear trendline are not presented, as they would not accurately reflect an S-curve trajectory. The category of progress was determined based on author judgment, using multiple lines of evidence. See Appendix C and Jaeger et al. (2023) for more information.

Sources: Authors' analysis based on data sources listed in each section.

Appendices

Appendix A.

Summary of Acceleration Factors

TABLE A-1 | Summary of Acceleration Factors

INDICATOR	MOST RECENT DATA POINT (year)	2030 TARGET	2035 TARGET	2050 TARGET	LIKELIHOOD OF FOLLOWING AN S-CURVE	AVERAGE ANNUAL RATE OF HISTORICAL CHANGE (Most recent five years of data for most indicators)	AVERAGE ANNUAL RATE OF CHANGE REQUIRED TO MEET 2030 TARGET (Estimated from the most recent year of data to 2030)	ACCELERATION FACTOR (How much the pace of recent average annual change needs to accelerate to achieve 2030 targets)[a]	STATUS (Based on acceleration factors and, in some cases, expert judgment)
Power									
Share of zero-carbon sources in electricity generation (%)[b]	39 (2022)	88–91	98–99 (2040)	99–100	∫	0.81 (2018–22)	6.3	8x[c]	!
Share of coal in electricity generation (%)	36 (2022)	4	0–1 (2040)	0	⇗	-0.54 (2018–22)	-3.9	7x	✕
Share of unabated fossil gas in electricity generation (%)	23 (2022)	5–7	1 (2040)	0	⇗	-0.20 (2018–22)	-2.1	>10x	✕
Carbon intensity of electricity generation (gCO_2/kWh)	440 (2022)	48–80	2–6 (2040)	<0[d]	⇗	-5.4 (2018–22)	-47	9x	✕
Buildings									
Energy intensity of building operations (kWh/m^2)	140 (2022)	85–120	N/A	55–80	↗	-1.8 (2018–22)	-5.3	3x	✕
Carbon intensity of building operations ($kgCO_2/m^2$)	38 (2022)	13–16	N/A	0–2	⇗	-0.77 (2018–22)	-2.9	4x	✕
Retrofitting rate of buildings (%/yr)	<1 (2019)	2.5–3.5	3.5 (2040)[f]	N/A	↗	Insufficient data	0.18	Insufficient data	?
Share of new buildings that are zero-carbon in operation (%)	5 (2020)	100	100	100	⇗	Insufficient data	9.5	Insufficient data	?
Industry									
Share of electricity in the industry sector's final energy demand (%)	29 (2021)[e]	35–43	51–54 (2040)	60–69	⇗	0.27 (2017–21)	1.1	4x	✕
Carbon intensity of global cement production ($kgCO_2$/t cement)	660 (2020)[f]	360–370[f]	N/A	55–90[f]	⇗	-1.4 (2016–20)	-29	>10x	✕
Carbon intensity of global steel production ($kgCO_2$/t crude steel)[g]	1890 (2020)[f,h]	1340–50[f]	N/A	0–130[f]	⇗	5 (2016–20)	-55	N/A; U-turn needed	↶
Green hydrogen production (Mt)	0.027 (2021)	58[i]	N/A	330[i]	∫	0.0052 (2017–21)	6.4	>10x[c]	✕
Transport									
Number of kilometers of rapid transit per 1 million inhabitants (km/1M inhabitants)	19 (2020)	38	N/A	N/A	↗	0.34 (2015–20)	1.9	6x[j]	✕

TABLE A-1 | Summary of Acceleration Factors (continued)

INDICATOR	**MOST RECENT DATA POINT** (year)	**2030 TARGET**	**2035 TARGET**	**2050 TARGET**	**LIKELIHOOD OF FOLLOWING AN S-CURVE**	**AVERAGE ANNUAL RATE OF HISTORICAL CHANGE** (Most recent five years of data for most indicators)	**AVERAGE ANNUAL RATE OF CHANGE REQUIRED TO MEET 2030 TARGET** (Estimated from the most recent year of data to 2030)	**ACCELERATION FACTOR** (How much the pace of recent average annual change needs to accelerate to achieve 2030 targets)[a]	**STATUS** (Based on acceleration factors and, in some cases, expert judgment)
Number of kilometers of high-quality bike lanes per 1,000 inhabitants (km/1,000 inhabitants)	0.0044 (2020)	2	N/A	N/A	↗	0.00072 (2015–20)	0.2	>10x[j]	✕
Share of kilometers traveled by passenger cars (% of passenger-km)[k]	45 (2019)	35–43	N/A	N/A	↗	1.4 (2015–19)	-0.57	N/A; U-turn needed[j]	↩
Share of electric vehicles in light-duty vehicle sales (%)	10 (2022)[l]	75–95	100	N/A	⤴	2.1 (2018–22)	9.4	4x[c]	✓
Share of electric vehicles in the light-duty vehicle fleet (%)	1.5 (2022)[l]	20–40	N/A	85–100	⤴	0.28 (2018–22)	3.6	>10x[c]	!
Share of electric vehicles in two- and three-wheeler sales (%)	49 (2022)[m]	85	N/A	100	⤴	3.6 (2018–22)	4.6	1.3x[c]	!
Share of battery electric vehicles and fuel cell electric vehicles in bus sales (%)	3.8 (2022)[n]	60	N/A	100	⤴	-0.53 (2018–22)	7	N/A; U-turn needed[c]	↩
Share of battery electric vehicles and fuel cell electric vehicles in medium- and heavy-duty commercial vehicle sales (%)	2.7 (2022)[n]	30	N/A	99	⤴	0.43 (2018–22)	3.4	8x[c]	✕
Share of sustainable aviation fuels in global aviation fuel supply (%)	0.1 (2022)	13	N/A	100	⤴	0.035 (2020–22)	1.6	>10[c]	✕
Share of zero-emissions fuels in maritime shipping fuel supply (%)	0 (2018)	5	N/A	93	⤴	0 (2017–21)	0.42	>10[c]	✕
Forests and Land[o]									
Deforestation (Mha/yr)	5.8 (2022)[p]	1.9	N/A	0.31	↗	-0.11 (2014–22)	-0.49	4x[q]	✕
Peatland degradation (Mha/yr)	0.06 (annual average, 1993–2018)	0	0	0	↗	Insufficient data	-0.005	Insufficient data	?
Mangrove loss (ha/yr)	32,000 (annual average, 2017–19)[r]	4,900	N/A	N/A	↗	950 (2008–19)	-2400	N/A; U-turn needed[s]	↩
Reforestation (total Mha)	130 (total gain, 2000–2020)	100 (2020–30)[t]	150 (2020-35)[t]	300 (2020–50)[t]	↗	6.5	10	1.5x[u]	!
Peatland restoration (total Mha)	0 (as of 2015)[v]	15 (2020–30)[t]	N/A	20–29 (2020–50)[t]	↗	Insufficient data	1	Insufficient data	?
Mangrove restoration (total ha)	15,000 (total direct gain, 1999–2019)[w]	240,000 (2020–30)[t]	N/A	N/A	↗	750	24,000	>10[x]	✕

TABLE A-1 | Summary of Acceleration Factors (continued)

INDICATOR	MOST RECENT DATA POINT (year)	2030 TARGET	2035 TARGET	2050 TARGET	LIKELIHOOD OF FOLLOWING AN S-CURVE	AVERAGE ANNUAL RATE OF HISTORICAL CHANGE (Most recent five years of data for most indicators)	AVERAGE ANNUAL RATE OF CHANGE REQUIRED TO MEET 2030 TARGET (Estimated from the most recent year of data to 2030)	ACCELERATION FACTOR (How much the pace of recent average annual change needs to accelerate to achieve 2030 targets)[a]	STATUS (Based on acceleration factors and, in some cases, expert judgment)
Food and Agriculture									
GHG emissions intensity of agricultural production (gCO$_2$e/1,000 kcal)	700 (2020)	500	450	320	↗	-7.2 (2016–20)	-20	3x	✕
Crop yields (t/ha)	6.6 (2021)	7.8	8.2	9.6	↗	0.009 (2017–21)	0.13	>10x	✕
Ruminant meat productivity (kg/ha)	29 (2021)	33	35	42	↗	0.42 (2017–21)	0.49	1.2x	!
Share of food production lost (%)[y]	13 (2021)	6.5	6.5	6.5	↗	0.054 (2016–21)	-0.75	N/A; U-turn needed[z]	⮏
Food waste (kg/capita)[aa]	120 (2019)	61	61	61	↗	Insufficient data	-5.5	Insufficient data	?
Ruminant meat consumption (kcal/capita/day)[bb]	91 (2020)[cc]	79	74	60	↗	-0.15 (2016–20)	-1.2	8x	✕
Technological Carbon Removal									
Technological carbon removal (MtCO$_2$/yr)	0.57 (2022)	30–690	N/A	740–5,500	⇗	0.002 (2018-22)	45	>10x	✕
Finance									
Global total climate finance (trillion US$/yr)[dd]	0.85 (2021)	5.2	N/A	5.1	↗	0.062 (2017–21)	0.49	8x	✕
Global public climate finance (trillion $/yr)[ee]	0.332 (2020)	1.31–2.61	N/A	1.29–2.57	↗	0.019 (2016–20)	0.16	8x	✕
Global private climate finance (trillion $/yr)[ee]	0.333 (2020)	2.61–3.92	N/A	2.57–3.86	↗	0.027 (2016–20)	0.29	>10x	✕
Ratio of investment in low-carbon to fossil fuel energy supply	1:1 (2023)	7:1	10:1 (2040)	10:1	↗	0.06 (2019–23)	0.85	>10x	✕
Share of global GHG emissions under mandatory corporate climate risk disclosure (%)[ff]	20 (2022)	75	N/A	100	↗	4.4 (2018–22)	6.8	1.5x	!
Weighted average carbon price in jurisdictions with emissions pricing systems (2015$/tCO$_2$e)	23 (2023)	170–290	N/A	430–990	↗	2.4 (2019–23)	30	>10x	✕
Total public financing for fossil fuels (billion $/yr)	1,100 (2021)[gg]	0	0	0	↗	44 (2017–21)	-120	N/A; U-turn needed	⮏

Notes: gCO$_2$/kWh = grams of carbon dioxide per kilowatt-hour; gCO$_2$e/1,000 kcal = grams of carbon dioxide equivalent per 1,000 kilocalories; GHG = greenhouse gas; ha/yr = hectares per year; kcal/capita/day = kilocalories per capita per day; kg/capita = kilograms per capita; kgCO$_2$/m^2 = kilogram of carbon dioxide per square meter; kgCO$_2$/t = kilograms of carbon dioxide per tonne; kg/ha = kilograms per hectare; km/1M inhabitants = kilometers per 1 million inhabitants; km/1,000 inhabitants = kilometers per 1,000 inhabitants; kWh/m^2 = kilowatt-hour per square meter; Mha/yr = million hectares per year; Mt = million tonnes; MtCO$_2$/yr = million tonnes of carbon dioxide per year; passenger-km = passenger-kilometers; tCO$_2$e = tonne of carbon dioxide equivalent; t/ha = tonnes per hectare; yr = year. See Jaeger et al. (2023) for more information on methods for selecting targets, indicators, and datasets, as well as our approach for assessing progress.

TABLE A-1 | Summary of Acceleration Factors (continued)

[a] For acceleration factors between 1 and 2, we round to the 10th place (e.g., 1.2 times); for acceleration factors between 2 and 3, we round to the nearest half number (e.g., 2.5 times); for acceleration factors between 3 and 10, we round to the nearest whole number (e.g., 7 times); and acceleration factors higher than 10, we note as >10.

[b] Zero-carbon sources include solar, wind, hydropower, geothermal, nuclear, marine, and biomass technologies.

[c] For indicators categorized as S-curve likely, acceleration factors calculated using a linear trendline are not presented in the report, as they would not accurately reflect an S-curve trajectory. The category of progress was determined based on author judgment, using multiple lines of evidence. See Appendix C and Jaeger et al. (2023) for more information.

[d] Achieving below zero–carbon intensity implies biomass power generation with carbon capture and storage. These targets limit bioenergy with carbon capture and storage use to 5 $GtCO_2$ per year in 2050. See Jaeger et al. (2023) for more information about the sustainability criteria used in target-setting.

[e] Historical data from IEA (2023l) accessed with a paid license to the IEA's datasets.

[f] Targets and historical emissions data include direct and indirect GHG emissions.

[g] The carbon intensity of steel production accounts for both primary and secondary steel.

[h] The 2021 data point from the World Steel Association is not included due to a change in the methodology to derive the data.

[i] The targets refer to what is needed for the whole economy to decarbonize and thus not only for the industry sector.

[j] Due to data limitations, an acceleration factor was calculated for this indicator using methods from Boehm et al. (2021).

[k] We calculated this number using the share of passenger-kilometers traveled in light-duty vehicles.

[l] These data differ from those of previous installments of the *State of Climate Action* in that they show only battery electric vehicles and exclude plug-in hybrid vehicles to align historical data with the 2030, 2035, and 2050 targets. We now use data from IEA (2023e).

[m] Historical data from BloombergNEF (2023), accessed with permission from Bloomberg New Energy Finance.

[n] These data differ from those included in previous installments of the *State of Climate Action*. We now use data from IEA (2023e) to align historical data with the 2030 and 2050 targets.

[o] Historical data for forests and land indicators were estimated using maps derived from remotely sensed data, and accordingly, they contain a degree of uncertainty. See Jaeger et al. (2023) for more information on the known limitations of each.

[p] See Jaeger et al. (2023) and Box 5 in Boehm et al. (2022) for a description of methods used to estimate deforestation.

[q] Indicators for forests and land experience high interannual variability in historical data due to both anthropogenic and natural causes. Accordingly, 10 years instead of 5 years was used to calculate the linear trendline where possible. For this indicator, however, an 8-year trendline was calculated, using data from 2015 to 2022 due to temporal inconsistencies in the data before and after 2015 (Weisse and Potapov 2021).

[r] Historical data from Murray et al. (2022), which estimated gross mangrove area lost from 1999 to 2019, was broken into three-year epochs. Loss for each epoch was divided by the number of years in the epoch to determine the average annual loss rate.

[s] Indicators for forests and land experience high interannual variability in historical data due to both anthropogenic and natural causes. Accordingly, 10 years instead of 5 years was used to calculate the linear trendline where possible. For this indicator, however, a 12-year trendline was calculated, using data from 2008 to 2019 to account for the full range of years included in four 3-year epochs from Murray et al. (2022). To estimate the average annual loss rate from 2008 to 2019, gross loss was divided by the number of years in each epoch.

[t] Reforestation, peatland restoration, and mangrove restoration targets are additional to any reforestation and restoration that occurred prior to 2020, and these targets are cumulative from either 2020 to 2030 or 2020 to 2050.

[u] Following Boehm et al. (2021) and due to data limitations, the average annual rate of change across the most recently available time period (2000–2020) was used to estimate the historical rate of change, rather than a linear trendline.

[v] Peatland restoration targets were adapted from Humpenöder et al. (2020) and Roe et al. (2021), which assume that 0 Mha of peatlands globally were rewetted as of 2015. This assumption, however, does not suggest that peatland restoration has not occurred, as there is evidence of rewetting, for example, in Canada, Indonesia, and Russia (UNEP 2022b; Sirin 2022; BRGM 2023), but rather speaks to the lack of global data on peatland restoration.

[w] Murray et al. (2022) estimated that a gross area of 180,000 ha (95 percent confidence interval of 0.09 to 0.30 Mha) of mangrove gain occurred from 1999 to 2019, only 8 percent of which can be attributed to direct human activities, such as mangrove restoration or planting. We estimated the most recent data point for mangrove restoration by taking 8 percent of the total mangrove gain from 1999 to 2019 (15,000 ha). See Jaeger et al. (2023) for more information.

[x] Following Boehm et al. (2021) and due to data limitations, the average annual rate of change across the most recently available time period (1999–2019) was used to estimate the historical rate of change, rather than a linear trendline.

[y] Food loss occurs before food gets to market.

[z] Due to data limitations, an acceleration factor was calculated for this indicator using a linear trendline estimated with three data points across six years.

[aa] Food waste occurs at the retail level and in homes and restaurants, among other locations.

[bb] This diet shift applies specifically to the high-consuming regions (Americas, Europe, and Oceania). It does not apply to populations within the Americas, Europe, and Oceania that already consume less than 60 kcal/capita/day, have micronutrient deficiencies, and/or do not have access to affordable and healthy alternatives to ruminant meat.

[cc] Consumption data are given in availability, which is the per capita amount of ruminant meat available at the retail level and is a proxy for consumption.

[dd] This indicator includes public and private, as well as domestic and international, flows.

[ee] These indicators include both domestic and international flows.

[ff] Jurisdictions included in 2022 are Brazil, Egypt, India, Japan, New Zealand, Singapore, Switzerland, the United Kingdom, and the European Union. Disclosure requirements are not uniform among countries and apply to different or select types of firms (e.g., financial institutions or publicly traded firms) with diverse implementation timelines. We consider jurisdictions that implemented any form of mandatory requirement during the year it was approved, even if it enters into force in phases with different timelines. This approach can result in an overestimation, as implementation timelines are enforced over the years in different stages.

[gg] Data are a compilation of production and consumption subsidies, G20 state-owned entity fossil fuel capital expenditure, and international public fossil fuel finance from multilateral development banks and G20 countries' development finance institutions and export credit agencies.

Source: Authors' analysis based on data sources listed in each section.

Appendix B.

Changes in Acceleration Factors and Categories of Progress between State of *Climate Action 2022* and *State of Climate Action 2023*

Table B-1 indicates if and why each indicator's acceleration factor and category of progress changed from the *State of Climate Action 2022* (Boehm et al. 2022) to the *State of Climate Action 2023*. For most indicators, a combination of several factors, such as target changes, an additional year of data, or changes in underlying datasets, likely spurred these differences. And while it is difficult to disentangle these effects, we identify several key explanations for each indicator.

1. Target change. For some indicators, the target itself has changed. This means that, in the *State of Climate Action 2023*, the goal toward which progress is measured differs from the goal in last year's report. As such, acceleration factors and categories of progress for these indicators are not directly comparable to last year's report. The reasons for changing individual targets are described further in our updated, complementary technical note (Jaeger et al. 2023).

2. Data change. A change in historical data between the 2022 and 2023 reports—either through the addition of just one new data point or through switching the full historical dataset due to new availability of an improved source—impacts the acceleration factor in two ways. First, the 5-year (or 10-year) trendline changes with a new data point and/or different data. Second, the average annual rate of change needed to reach the 2030 target changes as we get closer to 2030 with an additional year of data. Hence, every change in data affects the acceleration factor. In Table B-1, we indicate whether we switched to a new dataset or whether a new data point was added for each indicator.

Finally, some indicators and targets have been established in this report that we did not track in previous iterations of the series. These indicators are labeled as **new indicator**. For others, we adjusted the indicator to better reflect the latest, best available science or to match a newly published data source. We label these indicators as **updated indicator**. Finally, for still more indicators, we observe no change between the reports, and accordingly, we label these as **no difference**.

When this report features new or revised targets and indicators relative to the State of Climate Action 2022, we note these changes as a first-order explanation of differences between the assessments of progress across both publications. However, in some instances, underlying historical data have changed as well.

TABLE B-1 | Changes in acceleration factor and category of progress between *State of Climate Action 2022* and *State of Climate Action 2023*

2023 INDICATOR	SOCA 2022 ACCELERATION FACTOR	SOCA 2022 STATUS	SOCA 2023 ACCELERATION FACTOR[a]	SOCA 2023 STATUS	EXPLANATION OF DIFFERENCES BETWEEN 2022 AND 2023
Power					
Share of zero-carbon sources in electricity generation (%)[b]	6x	!	8x[c]	!	Target change
Share of coal in electricity generation (%)	6x	✕	7x	✕	Target change
Share of unabated fossil gas in electricity generation (%)	N/A; U-turn needed	↩	>10x	✕	Target change
Carbon intensity of electricity generation (gCO_2/kWh)	5x	✕	9x	✕	Target change
Buildings					
Energy intensity of building operations (kWh/m^2)	7x / 5x (residential/ commercial)	✕	3x	✕	Updated indicator

TABLE B-1 | Changes in acceleration factor and category of progress between *State of Climate Action 2022* and *State of Climate Action 2023* (continued)

2023 INDICATOR	SOCA 2022 ACCELERATION FACTOR	SOCA 2022 STATUS	SOCA 2023 ACCELERATION FACTOR[a]	SOCA 2023 STATUS	EXPLANATION OF DIFFERENCES BETWEEN 2022 AND 2023
Carbon intensity of building operations (kgCO$_2$/m^2)	Insufficient data	?	4x	✕	Updated indicator
Retrofitting rate of buildings (%/yr)	Insufficient data	?	Insufficient data	?	No difference
Share of new buildings that are zero-carbon in operation (%)	N/A	N/A	Insufficient data	?	New indicator
Industry					
Share of electricity in the industry sector's final energy demand (%)	1.7x	!	4x	✕	Target change
Carbon intensity of global cement production (kgCO$_2$/t cement)	>10x	✕	>10x	✕	No difference
Carbon intensity of global steel production (kgCO$_2$/t crude steel)[d]	N/A; U-turn needed	↶	N/A; U-turn needed	↶	No difference
Green hydrogen production (Mt)	>10x	✕	>10x[c]	✕	Target change
Transport					
Number of kilometers of rapid transit per 1 million inhabitants (km/1M inhabitants)	6x	✕	6x[e]	✕	No difference
Number of kilometers of high-quality bike lanes per 1,000 inhabitants (km/1,000 inhabitants)	>10x	✕	>10x[e]	✕	No difference
Share of kilometers traveled by passenger cars (% of passenger-km)[f]	N/A; U-turn needed	↶	N/A; U-turn needed[e]	↶	No difference
Share of electric vehicles in light-duty vehicle sales (%)	5x	!	4x[c]	✓	Data change; new dataset[g]
Share of electric vehicles in the light-duty vehicle fleet (%)	>10x	✕	>10x[c]	!	Data change; new dataset[g]
Share of electric vehicles in two- and three-wheeler sales (%)	N/A	N/A	1.3x[c]	!	New indicator
Share of battery electric vehicles and fuel cell electric vehicles in bus sales (%)	>10x	!	N/A; U-turn needed[c]	↶	Data change; new dataset[h]

TABLE B-1 | Changes in acceleration factor and category of progress between *State of Climate Action 2022* and *State of Climate Action 2023* (continued)

2023 INDICATOR	SOCA 2022 ACCELERATION FACTOR	SOCA 2022 STATUS	SOCA 2023 ACCELERATION FACTOR[a]	SOCA 2023 STATUS	EXPLANATION OF DIFFERENCES BETWEEN 2022 AND 2023
Share of battery electric vehicles and fuel cell electric vehicles in medium- and heavy-duty commercial vehicle sales (%)	Insufficient data	✖	8x[c]	✖	Data change; new dataset[h]
Share of sustainable aviation fuels in global aviation fuel supply (%)	Insufficient data	✖	Insufficient data[c]	✖	Target change
Share of zero-emissions fuels in maritime shipping fuel supply (%)	Insufficient data	✖	Insufficient data[c]	✖	Target change
Forests and Land					
Deforestation (Mha/yr)	2.5x	✖	4x[i]	✖	Data change; additional year(s) of data
Peatland degradation (Mha/yr)	Insufficient data	?	Insufficient data	?	No difference
Mangrove loss (ha/yr)	N/A; U-turn needed	⤵	N/A; U-turn needed[j]	⤵	No difference
Reforestation (total Mha)	1.5x	!	1.5x[k]	!	No difference
Peatland restoration (total Mha)	Insufficient data	?	Insufficient data	?	No difference
Mangrove restoration (total ha)	Insufficient data	?	>10x[l]	✖	Data change; new dataset[m]
Food and Agriculture					
GHG emissions intensity of agricultural production (gCO_2e/1,000 kcal)	N/A	N/A	3x	✖	Updated indicator[n]
Crop yields (t/ha)	6x	✖	>10x	✖	Data change; additional year(s) of data
Ruminant meat productivity (kg/ha)	1.3x	!	1.2x	!	Data change; additional year(s) of data
Share of food production lost (%)[o]	Insufficient data	?	N/A; U-turn needed[p]	⤵	Data change; additional year(s) of data
Food waste (kg/capita)[q]	Insufficient data	?	Insufficient data	?	No difference

TABLE B-1 | Changes in acceleration factor and category of progress between *State of Climate Action 2022* and *State of Climate Action 2023* (continued)

2023 INDICATOR	SOCA 2022 ACCELERATION FACTOR	SOCA 2022 STATUS	SOCA 2023 ACCELERATION FACTOR[a]	SOCA 2023 STATUS	EXPLANATION OF DIFFERENCES BETWEEN 2022 AND 2023
Ruminant meat consumption (kcal/capita/day)[r]	5x	☒	8x	☒	Data change; additional year(s) of data
Technological Carbon Removal					
Technological carbon removal ($MtCO_2$/yr)	>10x	☒	>10x	☒	Target change
Finance					
Global total climate finance (trillion US$/yr)[s]	>10x	☒	8x	☒	Data change; additional year(s) of data
Global public climate finance (trillion $/yr)[t]	>10x	☒	8x	☒	Data change; additional year(s) of data
Global private climate finance (trillion $/yr)[t]	>10x	☒	>10x	☒	No difference
Ratio of investment in low-carbon to fossil fuel energy supply	N/A	N/A	>10x	☒	New indicator
Share of global GHG emissions under mandatory corporate climate risk disclosure (%)[u]	>10x	☒	1.5x	❗	Target change
Weighted average carbon price in jurisdictions with emissions pricing systems (2015$/$tCO_2$e)	8x	☒	>10x	☒	Updated indicator[v]
Total public financing for fossil fuels (billion $/yr)	5x	☒	N/A; U-turn needed	⮌	Data change; additional year(s) of data

Notes: gCO_2/kWh = grams of carbon dioxide per kilowatt-hour; gCO_2e/1,000 kcal = grams of carbon dioxide equivalent per 1,000 kilocalories; GHG = greenhouse gas; ha/yr = hectares per year; kcal/capita/day = kilocalories per capita per day; kg/capita = kilograms per capita; $kgCO_2/m^2$ = kilogram of carbon dioxide per square meter; $kgCO_2$/t = kilograms of carbon dioxide per tonne; kg/ha = kilograms per hectare; km/1M inhabitants = kilometers per 1 million inhabitants; km/1,000 inhabitants = kilometers per 1,000 inhabitants; kWh/m^2 = kilowatt-hour per square meter; Mha/yr = million hectares per year; Mt = million tonnes; $MtCO_2$/yr = million tonnes of carbon dioxide per year; passenger-km = passenger-kilometers; SoCA = State of Climate Action; tCO_2e = tonne of carbon dioxide equivalent; t/ha = tonnes per hectare; yr = year. See Jaeger et al. (2023) for more information on methods for selecting targets, indicators, and datasets, as well as our approach for assessing progress.

[a] For acceleration factors between 1 and 2, we round to the 10th place (e.g., 1.2 times); for acceleration factors between 2 and 3, we round to the nearest half number (e.g., 2.5 times); for acceleration factors between 3 and 10, we round to the nearest whole number (e.g., 7 times); and acceleration factors higher than 10, we note as >10.

[b] Zero-carbon sources include solar, wind, hydropower, geothermal, nuclear, marine, and biomass technologies.

[c] For indicators categorized as S-curve likely, acceleration factors calculated using a linear trendline are not presented in the report, as they would not accurately reflect an S-curve trajectory. The category of progress was determined based on author judgment, using multiple lines of evidence. See Appendix C and Jaeger et al. (2023) for more information.

[d] The carbon intensity of steel production accounts for both primary and secondary steel.

[e] Due to data limitations, an acceleration factor was calculated for this indicator using methods from Boehm et al. (2021).

[f] We calculated this number using the share of passenger-kilometers traveled in light-duty vehicles.

[g] These data differ from those of previous installments of the *State of Climate Action* in that they show only battery electric vehicles and exclude plug-in hybrid vehicles to align historical data with the 2030, 2035, and 2050 targets. We now use data from IEA (2023e).

TABLE B-1 | Changes in acceleration factor and category of progress between *State of Climate Action 2022* and *State of Climate Action 2023* (continued)

[h] These data differ from those in previous installments of the *State of Climate Action.* We now use data from IEA (2023e) to align historical data with the 2030 and 2050 targets.

[i] Indicators for forests and land experience high interannual variability in historical data due to both anthropogenic and natural causes. Accordingly, 10 years instead of 5 years was used to calculate the linear trendline where possible. For this indicator, however, an 8-year trendline was calculated, using data from 2015 to 2022 due to temporal inconsistencies in the data before and after 2015 (Weisse and Potapov 2021).

[j] Indicators for forests and land experience high interannual variability in historical data due to both anthropogenic and natural causes. Accordingly, 10 years instead of 5 years was used to calculate the linear trendline where possible. For this indicator, however, a 12-year trendline was calculated, using data from 2008 to 2019 to account for the full range of years included in four 3-year epochs from Murray et al. (2022). To estimate the average annual loss rate from 2008 to 2019, gross loss was divided by the number of years in each epoch.

[k] Following Boehm et al. (2021) and due to data limitations, the average annual rate of change across the most recently available time period (2000–2020) was used to estimate the historical rate of change, rather than a linear trendline.

[l] Following Boehm et al. (2021) and due to data limitations, the average annual rate of change across the most recently available time period (1999–2019) was used to estimate the historical rate of change, rather than a linear trendline.

[m] Murray et al. (2022) estimated that a gross area of 180,000 ha (95 percent confidence interval of 0.09 to 0.30 Mha) of mangrove gain occurred from 1999 to 2019, only 8 percent of which can be attributed to direct human activities, such as mangrove restoration or planting. We estimated the most recent data point for mangrove restoration by taking 8 percent of the total mangrove gain from 1999 to 2019 (15,000 ha). We now use these data to calculate an acceleration factor, which Boehm et al. 2022 did not do.

[n] We converted our prior indicator on GHG emissions from agricultural production to an indicator on GHG emissions intensity of agricultural production to better match the other food and agriculture indicators, which are all intensity metrics.

[o] Food loss occurs before food gets to market.

[p] Due to data limitations, an acceleration factor was calculated for this indicator using a linear trendline estimated with three data points across six years.

[q] Food waste occurs at the retail level and in homes and restaurants, among other locations.

[r] This diet shift applies specifically to the high-consuming regions (Americas, Europe, and Oceania). It does not apply to populations within the Americas, Europe, and Oceania that already consume less than 60 kcal/capita/day, have micronutrient deficiencies, and/or do not have access to affordable and healthy alternatives to ruminant meat.

[s] This indicator includes public and private, as well as domestic and international, flows.

[t] These indicators include both domestic and international flows.

[u] Jurisdictions included in 2022 are Brazil, Egypt, India, Japan, New Zealand, Singapore, Switzerland, the United Kingdom, and the European Union. Disclosure requirements are not uniform among countries and apply to different or select types of firms (e.g., financial institutions or publicly traded firms) with diverse implementation timelines. We consider jurisdictions that implemented any form of mandatory requirement during the year it was approved, even if it enters into force in phases with different timelines. This approach can result in an overestimation, as implementation timelines are enforced over the years in different stages.

[v] We converted our prior indicator on median carbon price in jurisdictions with pricing systems to an indicator on weighted average carbon price in jurisdictions with emissions with pricing systems to better account for the percentage of global GHG emissions covered by each carbon price for each year.

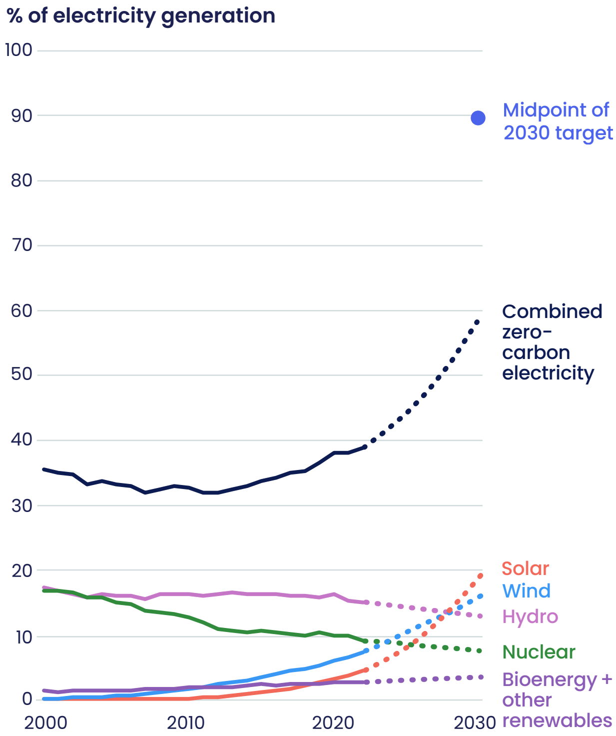
Source: Authors' analysis based on data sources listed in each section.

Appendix C.

Assessment of Progress for "S-Curve Likely" Indicators

Table C-1 presents our analysis for the nine S-curve likely indicators, following the methodology described in Jaeger et al. (2023). More specifically, to place each indicator into either the emergence, breakthrough, diffusion, or reconfiguration stage of an S-curve, we fitted different types of trendlines to historical data to determine the best fit, as well as estimated each indicator's current value as a percentage of its theoretical saturation value. For indicators in the breakthrough, diffusion, or reconfiguration stage with sufficient available data, we then fitted an S-curve to the historical data to inform author judgment to identify the category or progress for each indicator. This was possible for the share of zero-carbon sources in electricity generation (Figure C-1) and the share of electric vehicles in light-duty vehicle sales (Figure C-2). For all indicators, we also reviewed the literature, consulted with experts, and calculated the category of progress based on a linear trendline to inform author judgment.

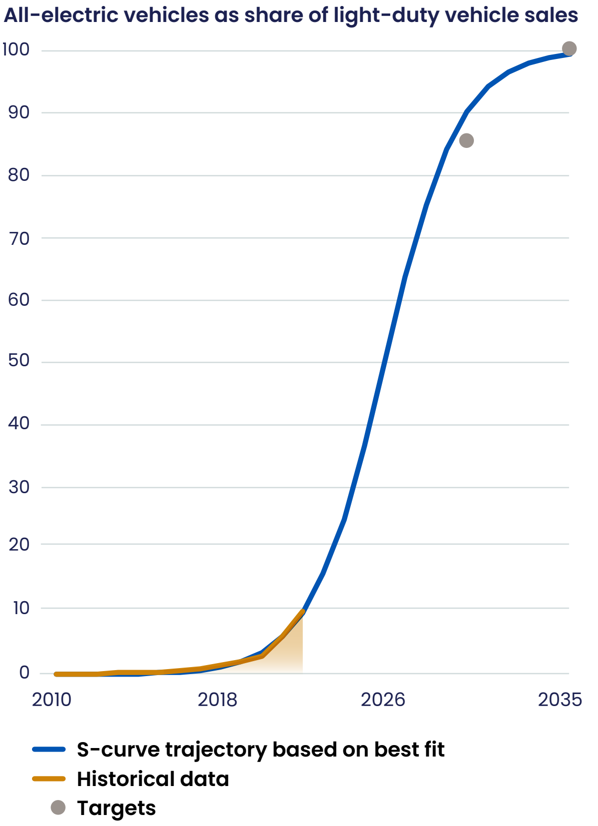
FIGURE C-1 | Share of zero-carbon sources in electricity generation: S-curve analysis for solar and wind



Notes: For the post-2022 trajectory, we assume that solar and wind continue along S-curves fit to the historical data. For solar, we assumed the saturation point was 64 percent of the electricity mix, and for wind we assumed the saturation point was 32 percent of the electricity mix. Collectively, these add up to 96 percent, which is the upper bound of our 2050 target for solar and wind. For hydro, nuclear, bioenergy, and other renewables, we assumed they continue along a linear trajectory.

Sources: Historical data from Ember (2023). Extrapolation by authors.

FIGURE C-2 | Electric vehicles as share of light-duty vehicle sales: S-curve analysis



Notes: For the post-2022 trajectory, we assumed that EV sales continue along an S-curve fit to the historical data with a saturation value of 100 percent. We also show the midpoint of the target range for 2030 here.

Sources: Historical data from IEA (2023f). Extrapolation by authors.

TABLE C-1 | Additional analysis for “S-curve likely” indicators

WHICH TRENDLINE REPRESENTS THE BEST FIT FOR THE LAST FIVE YEARS OF DATA?	WHAT PERCENTAGE OF THE SATURATION VALUE DOES THE MOST RECENT DATA POINT REPRESENT?	WHAT STAGE OF S-CURVE IS THE TECHNOLOGY IN?	WHAT WAS OUR S-CURVE ANALYSIS?	WHAT OTHER LINES OF EVIDENCE WERE CONSIDERED?	WHAT IS THE STATUS USING A LINEAR TRENDLINE?	WHAT IS THE STATUS USING AUTHOR JUDGMENT?
Share of zero-carbon sources in electricity generation (%)						
Because this indicator describes a set of related technologies, we examined trendlines for each technology separately. For solar, the exponential trendline was the best fit, while for wind, the linear trendline was the best fit. We do not expect nuclear, hydropower, and bioenergy to follow an S-curve, and, accordingly, the linear trendline was the best fit.	We assume that solar and wind together have a saturation value of 96 percent (the upper bound of our 2050 target). It is difficult to know how much of this would be from solar compared to wind, but we assume that solar makes up two-thirds and wind makes up one-third. In this case, solar power has a saturation value of 64 percent, and the current value of 4.6 percent is 7 percent of the saturation value. Wind power has a saturation value of 32 percent, and the current value of 7.3 percent is 23 percent of the saturation value. Even if our assumptions for the share of wind compared to the share of solar were different, both solar and wind are clearly greater than 5 percent of their respective saturation values and, thus, above the cutoff of the emergence stage.	Breakthrough stage for solar power, given that the indicator’s current value is greater than 5 percent of its saturation value and the historical trendline is exponential. Diffusion stage for wind power, given that the indicator’s current value is greater than 5 percent of its saturation value and the historical trendline is linear.	We fitted S-curves to the historical data for solar and wind and used linear trendlines for nuclear, hydropower, and bioenergy power. This combined trajectory indicates that the share of zero-carbon sources in electricity generation will reach 59 percent in 2030. This is less than half of the way from the current value to the midpoint of our 2030 target, which suggests that the indicator is well off track.	A recent report from RMI finds that if solar and wind follow a fast S-curve, they would reach 33 percent of electricity generation in 2030; if they follow pure exponential growth, they would reach 39 percent of electricity generation in 2030 (Bond et al. 2023). This is within striking distance of the IEA’s Net Zero Emissions (NZE) Scenario (IEA 2022t), which shows a 41 percent share of solar and wind in electricity generation by 2030, but well below this report’s target of 53–78 percent. The scenarios and literature that underpin this report’s targets show a higher share of total zero-carbon power and a higher share of wind and solar within zero-carbon power than the IEA’s NZE. This is because the IEA NZE shows strong growth in nuclear, fossil gas with carbon capture and storage, biomass, and hydropower generation. Additionally, the NZE has a higher overall carbon intensity of power generation than the average 1.5°C-compatible scenarios used in this report, which means that other sectors decarbonize faster in the NZE. IEA (2023i) finds solar power is “on track” for its net-zero emissions by 2050 scenario, but other zero-carbon technologies such as wind are classified as “more efforts needed.” Overall, the electricity system is classified as “more efforts needed.”	✖	❗
Green hydrogen production (Mt)						
A linear trendline is the best fit for the past five years of data, but an exponential trendline is the best fit for the past ten years of data.	Assuming green hydrogen production has a saturation value of 330 Mt (our 2050 target), the current value of 0.027 Mt is only 0.008 percent of the saturation value.	Emergence stage, given that the indicator’s current value is less than 5 percent of its saturation value.	S-curve fitting is too uncertain in the emergence stage. Given these uncertainties, we default to well off track unless there is compelling evidence to upgrade this indicator’s category of progress.	IEA (2023i) classifies green hydrogen as “more effort needed” to be consistent with its net-zero emissions by 2050 scenario. This category of progress is one step above the IEA’s “well off track” status. The IEA’s categories, however, are not identical to those in this report.	✖	✖

TABLE C-1 | Additional analysis for "S-curve likely" indicators (continued)

WHICH TRENDLINE REPRESENTS THE BEST FIT FOR THE LAST FIVE YEARS OF DATA?	WHAT PERCENTAGE OF THE SATURATION VALUE DOES THE MOST RECENT DATA POINT REPRESENT?	WHAT STAGE OF S-CURVE IS THE TECHNOLOGY IN?	WHAT WAS OUR S-CURVE ANALYSIS?	WHAT OTHER LINES OF EVIDENCE WERE CONSIDERED?	WHAT IS THE STATUS USING A LINEAR TRENDLINE?	WHAT IS THE STATUS USING AUTHOR JUDGMENT?
Share of electric vehicles in light-duty vehicle sales (%)						
Exponential	Assuming the share of EVs in light-duty vehicle sales has a saturation value of 100 percent (our 2035 target), the current value is only 10 percent of the saturation value.	Breakthrough stage, given that the indicator's current value is greater than 5 percent of its saturation value and the historical trendline is exponential.	We fitted an S-curve to the historical data, and this trajectory indicates that the share of EVs in light-duty vehicle sales will reach 93 percent by 2030. This suggests that the indicator is on track to achieve the midpoint of our 2030 target (see Figure 83, below).	IEA (2023i) classifies EVs as "on track" to achieve its net-zero emissions by 2050 scenario. But it does not specify whether this assessment refers to sales, fleet, or some other measure. Projections from IEA (2022t) and BloombergNEF (2022a) suggest that EV sales would be "off track" to reach their respective net-zero emissions scenarios, but both forecasts use linear projections, so we do not consider them.	✖	✔
Share of electric vehicles in the light-duty vehicle fleet (%)						
Exponential	Assuming the share of EVs in the light-duty vehicle fleet has a saturation value of 100 percent (the upper bound of our 2050 target), the current value is only 1.5 percent of the saturation value.	Emergence stage, given that the indicator's current value is less than 5 percent of its saturation value.	S-curve fitting is too uncertain in the emergence stage. Given these uncertainties, we default to well off track unless there is compelling evidence to upgrade this indicator's category of progress.	Strong growth in EV sales suggests a forthcoming breakthrough in EVs as a share of the LDV fleet. IEA (2023i) classifies EVs as "on track" to achieve its net-zero emissions by 2050 scenario. But it does not specify whether this assessment refers to sales, fleet, or some other measure. Projections from IEA (2022t) and BloombergNEF (2022a) suggest that EV fleet would be "off track" to reach their respective net-zero emissions scenarios, but both forecasts use linear projections, so we do not consider them. Although EV sales are on track for 2030 targets, EV fleet is not because new car sales do not necessarily correspond with equal removal of old cars from the market, and therefore the share of EVs on the road may lag well behind increases in sales (Keith et al. 2019). There is not enough evidence that the stock turnover will occur quickly enough to meet 2030 fleet goals, so this indicator remains off track.	✖	❗

TABLE C-1 | Additional analysis for “S-curve likely” indicators (continued)

WHICH TRENDLINE REPRESENTS THE BEST FIT FOR THE LAST FIVE YEARS OF DATA?	WHAT PERCENTAGE OF THE SATURATION VALUE DOES THE MOST RECENT DATA POINT REPRESENT?	WHAT STAGE OF S-CURVE IS THE TECHNOLOGY IN?	WHAT WAS OUR S-CURVE ANALYSIS?	WHAT OTHER LINES OF EVIDENCE WERE CONSIDERED?	WHAT IS THE STATUS USING A LINEAR TRENDLINE?	WHAT IS THE STATUS USING AUTHOR JUDGMENT?
Share of electric vehicles in two- and three-wheeler sales (%)						
Linear	Assuming the share of EVs in two- and three-wheeler sales has a saturation value of 100 percent (our 2050 target), the current value is 49 percent of the saturation value.	Diffusion stage, given that the indicator’s current value is greater than 5 percent of its saturation value and the historical trendline is linear.	N/A; data limitations prevented us from fitting an S-curve. Historical data begins at 34 percent in 2015, so we don’t know the shape of the curve from 0 percent to 34 percent. But given that the indicator is in the diffusion stage, in which change is roughly linear, we used the linear trendline to inform the judgment. The acceleration factor calculated using this trendline was 1.3x.	BloombergNEF (2022a) projects the share of EVs in two- and three-wheeler sales will increase from 43 percent in 2021 to 54 percent in 2030, which suggests that the indicator is well off track. These projections, however, do not account for the most recent data point of 49 percent in 2022.	!	!
Share of battery electric vehicles and fuel cell electric vehicles in bus sales (%)						
Linear	Assuming the share of battery electric vehicles and fuel cell electric vehicles in bus sales has a saturation value of 100 percent (our 2050 target), the current value is only 3.8 percent of the saturation value.	Emergence stage, given that the indicator’s current value is less than 5 percent of its saturation value. From 2015 to 2018, this indicator was above 5 percent, but it has since decreased, indicating that a barrier came up that prevented it from reaching a breakthrough.	S-curve fitting is too uncertain in the emergence stage. Given these uncertainties, we default to well off track unless there is compelling evidence to upgrade this indicator’s category of progress. Here, the data show that recent rates of change have been heading in the wrong direction entirely.	IEA (2023f) projects that EVs will account for 17 percent of bus sales in 2030, which suggests that the indicator is well off track.	⇩	⇩
Share of battery electric vehicles and fuel cell electric vehicles in medium- and heavy-duty commercial vehicle sales (%)						
Exponential	Assuming the share of battery electric vehicles and fuel cell electric vehicles in medium- and heavy-duty commercial vehicle sales has a saturation value of 99 percent (our 2050 target), the current value is only 2.7 percent of the saturation value.	Emergence stage, given that the indicator’s current value is less than 5 percent of its saturation value.	S-curve fitting is too uncertain in the emergence stage. Given these uncertainties, we default to well off track unless there is compelling evidence to upgrade this indicator’s category of progress.	BloombergNEF (2022a) projects that both medium- and heavy-duty EV sales will reach approximately 15 percent in 2030, which would be approximately half as much as what is needed to achieve our target of 30 percent. Note that BNEF’s projections include plug-in hybrid electric vehicles as well, so without including those their projections would likely be even lower.	✕	✕

TABLE C-1 | Additional analysis for “S-curve likely” indicators (continued)

WHICH TRENDLINE REPRESENTS THE BEST FIT FOR THE LAST FIVE YEARS OF DATA?	WHAT PERCENTAGE OF THE SATURATION VALUE DOES THE MOST RECENT DATA POINT REPRESENT?	WHAT STAGE OF S-CURVE IS THE TECHNOLOGY IN?	WHAT WAS OUR S-CURVE ANALYSIS?	WHAT OTHER LINES OF EVIDENCE WERE CONSIDERED?	WHAT IS THE STATUS USING A LINEAR TRENDLINE?	WHAT IS THE STATUS USING AUTHOR JUDGMENT?
Share of sustainable aviation fuels in global aviation fuel supply (%)						
Insufficient data	Assuming the share of sustainable aviation fuels in the global aviation fuel supply has a saturation value of 100 percent (our 2050 target), the current value is only 0.1 percent of the saturation value.	Emergence stage, given that the indicator’s current value is less than 5 percent of its saturation value.	S-curve fitting is too uncertain in the emergence stage. Given these uncertainties, we default to well off track unless there is compelling evidence to upgrade this indicator’s category of progress.	IEA (2023i) finds that aviation is “not on track” to achieve its net-zero emissions by 2050 scenario, although this assessment does not refer specifically to sustainable aviation fuels.	☒	☒
Share of zero-emissions fuels in maritime shipping fuel supply (%)						
Insufficient data	Assuming the share of zero-emissions fuels in maritime shipping fuel supply has a saturation value of 93 percent (our 2050 target), the current value is 0 percent of the saturation value.	Emergence stage, given that the indicator’s current value is less than 5 percent of its saturation value.	S-curve fitting is too uncertain in the emergence stage. Given these uncertainties, we default to well off track unless there is compelling evidence to upgrade this indicator’s category of progress.	IEA (2023i) finds that shipping is “not on track” to achieve its net-zero emissions by 2050 scenario, although this assessment does not refer specifically to zero-emissions fuels.	☒	☒

Notes: EV = electric vehicle; IEA = International Energy Agency; LDV = light-duty vehicle; Mt = million tonnes.

Source: Authors.

ENDNOTES

1. Wind, solar, nuclear, and some biomass electricity generation technologies are zero-carbon technologies in their operation, as are battery electric vehicles, battery electric planes, battery electric ships, and green hydrogen if the electricity they use is generated from zero-carbon sources. Other technologies that contribute to reducing emissions, such as those that help improve energy efficiency or facilitate electrification, are described as low-carbon in this report. Technologies that rely on carbon capture, utilization, and storage for any remaining emissions to achieve net zero, such as those used in cement production, are also described as low-carbon.

2. Note that this is different, and lower, than the ratio of total clean energy investment to fossil fuel investment, which also includes investments in energy efficiency and other end-use investments. The ratio of total clean energy to fossil fuel investment was 1.7:1 in 2023 (IEA 2023m). While investments in efficiency and electrifying end use are important, this indicator focuses on energy supply because end-use investments can be neutral to fuel source.

3. If implemented inappropriately, reforestation, peatland restoration, and mangrove restoration can generate adverse ecological effects. Planting alien species and/or monocultures, for example, threatens ecosystem integrity, while reforestation at higher latitudes, although beneficial for conserving biodiversity, provides few, if any, contributions to climate mitigation, as adding trees to these landscapes can alter the reflectivity of the planet's surface and produce a net warming effect (IPCC 2022b). But when broader landscape restoration principles are applied (e.g., by focusing on restoring entire landscapes, recovering ecological integrity, delivering multiple benefits, etc.), these harmful impacts can often be prevented. For example, reestablishing natural hydrological regimes across mangrove forests is often more successful in restoring these coastal ecosystems than planting saplings, alone (Lewis 2001, 2005).

4. The IPCC developed its category of "no and limited overshoot" pathways in its Special Report on Global Warming of 1.5°C. The IPCC's recent AR6 Working Group III report uses the same definition for its category C1 pathways, which are defined as follows: "Category C1 comprises modelled scenarios that limit warming to 1.5°C in 2100 with a likelihood of greater than 50%, and reach or exceed warming of 1.5°C during the 21st century with a likelihood of 67% or less. In this report, these scenarios are referred to as scenarios that limit warming to 1.5°C (>50%) with no or limited overshoot. Limited overshoot refers to exceeding 1.5°C global warming by up to about 0.1°C and for up to several decades" (IPCC 2022b). The report also notes that "scenarios in this category are found to have simultaneous likelihood to limit peak global warming to 2°C throughout the 21st century of close to and more than 90%" (IPCC 2022b).

5. Note that, while the IPCC treats agriculture, forestry, and other land uses as one sector, this report splits it into two sections: forests and land, as well as food and agriculture, given the number of indicators in each section.

6. Identifying shifts for each sector, as well as key changes needed to support the scale-up of carbon removal technologies and climate finance, is an inherently subjective exercise, as there are many possible ways to translate a global temperature goal into a set of individual actions. So long as the overall GHG emissions budget is maintained, a range of strategies (e.g., assigning more rapid and ambitious emissions-reduction targets to the power sector than to the transport sector or vice versa) can be pursued to limit global warming to 1.5°C. However, because the remaining GHG emissions budget is small, the degree of freedom to assign different weights to different sector-wide transformations that must occur is relatively limited, and the IPCC makes clear that, together, all sectors will eventually have to dramatically lower emissions to limit global warming to 1.5°C (IPCC 2022b). So, if a transformation across one sector is slower than this global requirement, another needs to transition proportionately faster, or additional CO2 must be removed from the atmosphere. Arguing that a sector needs more time for decarbonization, then, can only be done in combination with asserting that another can transition faster. A good starting point in translating these sector-wide transformations needed to limit global temperature rise to 1.5°C into a set of critical shifts is asking whether a sector can decarbonize by 2050. If so, how and how quickly, and, if not, why (CAT 2020a)?

7. A comprehensive assessment of equity and biodiversity is beyond the scope of the State of Climate Action series. See "Key Limitations" from Jaeger et al. (2023) for more information.

8. While the other Forests and Land indicators used a 10-year trendline, for our deforestation indicator we calculated an 8-year trendline using data from 2015 to 2022 due to temporal inconsistencies in the data before and after 2015 (Weisse and Potapov 2021).

9. Note that for the indicators with targets presented as a range, we assessed progress based on the midpoint of that range—that is, we compared the historical rates of change to the rates of change required to reach the midpoint. One exception is the median carbon price in jurisdictions with emissions with a pricing systems indicator; here, we calculated the acceleration factor required from a midpoint of $220/tCO2e within the 2030 range, as determined by IPCC (2022b).

10. For acceleration factors between 1 and 2, we rounded to the 10th place (e.g., 1.2 times); for acceleration factors between 2 and 3, we rounded to the nearest half number (e.g., 2.5 times); for acceleration factors between 3 and 10, we rounded to the nearest whole number (e.g., 7 times); and we noted acceleration factors higher than 10 as >10.

In previous reports, all acceleration factors under 10 were rounded to the 10th place (e.g., 7.4), which was too high a level of precision for the data available. Rounding to the nearest whole number is clearer and provides equivalent information about the pace of change needed.

11. In a change from the 2021 report, we no longer have a "stagnant" category. Indicators that were classified as stagnant in last year's report are now placed in the "well off track" or "wrong direction" category based on the linear trendline.

12. Zero-carbon power is defined as electricity generation by solar, wind, hydropower, nuclear, geothermal, marine, and biomass technologies, all of which generate negligible CO2 during their operational cycles.

13. Storage options such as batteries, pumped hydropower, or renewable hydrogen can help to smooth out fluctuations in the electricity supply, improve grid stability, and reduce the need for fossil fuel power plants to meet peak demand.

14. In a May 2022 communiqué, all G7 environment, climate, and energy ministers committed to achieving "predominately decarbonized electricity sectors" within their countries by 2035 (Clean Energy Wire 2022). However, the communiqué stopped short of setting a concrete date for exiting coal.

15. Adoption of any of these technologies entails trade-offs. Generating power from biomass, for example, is not inherently zero-carbon and requires adequate safeguards.

16. In addition to the levelized cost of electricity, which looks at the cost side of power generation, excluding factors such as government subsidies, system balancing costs, and market dynamics, it is also important to look at project revenues. However, these depend on a range of parameters that vary by location and sector.

17. Note that this indicator tracks total coal use, irrespective of whether it is combined with carbon capture and storage (CCS). This is a change from previous years, when we tracked only unabated coal (without CCS), because our analysis shows that coal with CCS is not a feasible solution for decarbonizing the power sector for a variety of reasons, and therefore would have a negligible role to play.

18. This indicator only tracks fossil gas with CCS, but it is important to note that the models used for determining benchmarks in this report show that gas with CCS only plays a minor role in decarbonization of the power sector, making up 0.1 percent of global power generation in 2030, 0.3 percent in 2040, and 0.5 percent in 2050. See Jaeger et al. (2023) for a more comprehensive overview of how targets for this indicator were developed.

19. The fugitive emissions associated with the production and value chain of fossil gas are often not properly accounted for, and are yet another reason to phase out gas as quickly as possible (Hendrick et al. 2016).

20. It is important to also continue tracking total power sector emissions to measure if overall electricity demand is increasing faster than the emissions intensity is falling.

21. Feed-in tariffs are payments to individual households or businesses adding electricity to the grid from renewable sources.

22. Pumped storage hydropower stores hydroelectric energy by pumping water from a lower reservoir to a higher one, then allowing it to flow back down through a turbine to generate power.

23. Achieving zero-carbon operational emissions in buildings will not be feasible for all buildings until the power grid is fully decarbonized. The IEA refers to buildings that would be decarbonized with a zero-emissions power grid as "zero carbon ready," while we term these zero-carbon based on the assumption that the power sector targets will be met and the buildings decarbonized if no on-site fossil fuels are used.

24. Such technologies may also include changes in raw materials, such as the increased use of scrap steel in steelmaking, and the use of supplementary cementitious materials in cement-making.

25. With current technologies, zero emissions in the cement sector are not achievable, and there likely will be residual emissions that need to be addressed to achieve net-zero emissions.

26. Achieving net-zero emissions in the global steel sector will likely require addressing residual emissions.

27. Including both primary and secondary steel production.

28. Recent developments suggest that the ambition level of the targets could be even further increased, particularly in the near term (MPP 2022b; Witecka et al. 2023; Bataille et al. 2021).

29. Green hydrogen–based DRI-EAF uses green hydrogen as the reducing agent (instead of coke) and therefore does not generate process emissions. It uses electricity and can thus also be fully decarbonized by ensuring that the power supply is clean. Similarly, iron ore electrolysis is a fully electrified production route where even the reduction of the iron ore is done with electricity.

30. Switching from fossil fuel–based DRI to hydrogen-based DRI requires repurposing the technology.

31. Hydrogen can be produced using different types of fuels and technologies. Green hydrogen is produced with renewablebased electricity facilitated by an electrolyzer and thus does not generate CO_2 emissions.

32. Electrification in some industries, such as steel, is already commercially available using electric arc furnaces. In others, such as cement, further development is needed.

33. The IFC is a global financial institution focusing on private sector development in developing countries.

34. Other studies suggest that even lower clinker-to-cement ratios are possible by using SCMs, down to 40 percent (Dixit et al. 2021).

35. Given the varying definitions of low-carbon steel, there is a need for emissions accounting methodologies to align for adoption of steel standards. This report uses the definition in the Green Steel Tracker to estimate the number of low-carbon steel projects.

36. These are preliminary numbers, as the latest version of the dataset was updated before the end of 2022.

37. We used the April 2023 version of the Green Steel Tracker dataset. Only steelmaking projects are considered, thus excluding hydrogen production projects. The figure for operational full-scale plants is 48 projects when also including pilot, demonstration, and research and development projects.

38. However, the dataset might not fully reflect recent developments in certain parts of the world where projects may be reported in languages other than English.

39. These also include currently natural gas–fed DRI plants that are planned to be converted to green or low-carbon hydrogen.

40. Assuming a capacity factor of 0.08.

41. 0.1–0.2 Mt annually by 2025 compared to about 0.009 Mt in 2021, based on data from IEA's Global Hydrogen Projects database.

42. Statistics provided by the International Energy Agency.

43. The terms "shared," "collective," and "active transport" refer to modes of transportation where either passengers ride with others, mobility assets are shared among multiple users (see Castellanos et al. 2021), or where nonmotorized vehicles are used.

44. Please note that these conclusions are drawn from the limited number of cities that we are aggregating and might not reflect the global standings.

45. Please note that last year's report had a number of 0.0077 for the year 2020. This reflects changes in the quality of the data coming from OpenStreetMaps, not a change in data or methodology.

46. On a life-cycle basis, electric vehicles already emit less than internal combustion engine vehicles, even when accounting for battery production and vehicle assembly (Bieker 2021). As the power sector decarbonizes, the emissions advantage of electric vehicles will only grow.

47. This target includes two- and three-wheelers in China, India, and Indonesia because they make up a substantial portion of the light-duty vehicle fleet in those countries (CAT 2020b). Two- and three-wheeler sales are not included in the historical data for this indicator due to data limitations.

48. In this report, "electric light-duty vehicles" refers to battery electric vehicles only and excludes plug-in hybrid vehicles.

49. Two-wheeler sales data in China shall be viewed with caution, as official data tracks factory shipments (including exports) and often includes pedal-electric bicycles and other vehicles with a top speed of less than 50 km/hour. Deriving data used here with a minimum top speed of 50 km/hour is therefore challenging (IEA 2023e).

50. The categorization of progress for this indicator differs significantly from the categorization in Boehm et al. (2022) because the data source has been updated to better align with the 2030 and 2050 targets.

51. Zero-emissions fuels are those that emit net-zero emissions on a life-cycle basis. These include green ammonia, green hydrogen, e-methanol, and synthetic e-fuels produced from renewable sources of energy.

52. According to IPBES (2019), nature refers to "the non-human world, including coproduced features, with particular emphasis on living organisms, their diversity, their interactions among themselves and with their abiotic environment," and it includes "all dimensions of biodiversity, species, genotypes, populations, ecosystems, communities, biomes, Earth life support's systems, and their associated ecological, evolutionary and biogeochemical processes."

53. GHG emissions from AFOLU generally include those from agricultural production, as well as land use, land-use change, and forestry. Boehm et al. (2022) relied on the mean of three bookkeeping models from IPCC (2022b), as presented in the "Global Carbon Budget 2020" (Friedlingstein et al. 2020), to estimate net anthropogenic CO_2 emissions from land use, land-use change, and forestry. But these estimates of net anthropogenic CO_2 emissions from land use, land-use change, and forestry have been revised downward (e.g., from 6.6 $GtCO_2$ to 4.5 $GtCO_2$ in 2019) since the publication of Working Group III's Contribution to AR6, and this update has impacted estimates of GHG emissions from AFOLU more broadly (e.g., estimates of GHG emissions were also revised downward from roughly 13 $GtCO_2e$ to 11 $GtCO_2e$ in 2019). More specifically, both the "Global Carbon Budget 2021" and "Global Carbon Budget 2022" feature improvements in land-use forcing data, as well as updated estimates of agricultural areas and newly incorporated land-cover maps from satellite remote sensing, that underpin two of the study's three bookkeeping models (Blue and Oscar). Together, these changes resulted in revised annual estimates of net CO_2 emissions downward, such that all bookkeeping models now show a decreasing trend in net CO_2 emissions from land use, land-use change, and forestry since the 1990s (Friedlingstein et al. 2022a, 2022b). Yet authors of the "Global Carbon Budget 2022" caution that the global land-use change data used as a modeling input do not include forest degradation, which poses an increasing threat to these ecosystems' carbon stocks, and they note that CO_2 emissions from degradation may soon surpass those from deforestation (e.g., Matricardi et al. 2020; Qin et al. 2021; Lapola et al. 2023).

54. Global databases, as well as methods to estimate net anthropogenic CO_2 emissions, differ on which CO_2 emissions and removals occurring on land can be defined as "anthropogenic." This section reports net anthropogenic CO_2 emissions as estimated by the mean of three global bookkeeping models, with supplementary data on emissions from peat burning and drainage (Minx et al. 2021; European Commission and JRC (2022), as used in the "Global Carbon Budget 2022" (Friedlingstein et al. 2022b). Note that these global estimates of net anthropogenic CO_2 emissions are higher than those from National Greenhouse Gas Inventories and FAOSTAT (Friedlingstein et al. 2022b). While no method is inherently preferable over another, this section follows the "Summary for Policymakers" in IPCC (2022b) in reporting the estimate from global bookkeeping models.

55. "Land-based mitigation measures" or "land-based measures" in Section 6, Forests and Land, focus on activities to protect, restore, and sustainably manage forests and other ecosystems. Land-based mitigation measures that focus on actions to reduce GHG emissions and enhance carbon removals across agricultural lands are discussed in Section 7, Food and Agriculture. The IPCC (2022b) finds that land-based mitigation measures from forests and other ecosystems that cost up to \$100/tCO_2e can deliver between 4.2 and 7.3 GtCO_2e per year from 2020 to 2050, with the bottom end of the range representing the median estimate from integrated assessment models and the top end of the range representing the median estimate from sectoral studies.

56. Following Roe et al. (2021), this report focuses solely on mangrove forests, rather than coastal wetlands more broadly.

57. The Tyukavina et al. (2022) data identify tree loss where fire was the direct driver of loss for each 30-meter loss pixel mapped by Hansen et al. (2013). This does not include loss where trees were removed prior to burning (e.g., burning felled trees to clear land for agriculture). It may include wildfires, escaped fires from human activities, and intentionally set fires, among others (Tyukavina et al. 2022).

58. Following Leifeld and Menichetti (2018), peatlands' soil carbon stocks are estimated to be roughly 640 GtC (Yu et al. 2010; Page et al. 2011; Dargie et al. 2017), and global carbon stocks down to depths of 3 meters are estimated to be about 3,000 GtC from Scharlemann et al. (2014).

59. There are four categories of organic soils, also known as histosols (Fibrists, Hemists, Saprists, and Folists), and, while peat is an organic soil, not all of these categories are peat. For example, both Fibrists and Hemists include peat, but Folist soils do not (IPS n.d.).

60. This global estimate of avoided emissions associated with this target to reduce mangrove loss does not account for non-CO_2 fluxes that may occur during conversion, representing one gap in the scientific community's understanding of the role that mangrove forests play in climate change mitigation (Macreadie et al. 2019).

61. These estimates of boreal, temperate, and tropical forest carbon density include carbon stored in aboveground and belowground biomass, as well as soil organic carbon within the top 30 centimeters. They range from 166 tonnes of carbon per hectare within tropical dry forests to 272 tonnes of carbon per hectare within temperate conifer forests. For mangrove forests, soil organic carbon within the top 100 centimeters is included, with the estimated carbon density of these ecosystems roughly 500 tonnes of carbon per hectare (Goldstein et al. 2020). When accounting for carbon stored at greater depths (i.e., down to one meter for forests and two meters for mangroves), mangrove carbon density is roughly four to six times higher than that of terrestrial forests (Temmink et al. 2022).

62. The wide range in estimates of total carbon stored in mangrove ecosystems is in part due to variability in the soil depth included in these estimates. The lower end of the range accounts for up to one meter of soil depth (Leal and Spalding 2022), while the higher end of the range accounts for up to two meters of soil depth (Temmink et al. 2022).

63. Estimates of gross mangrove loss vary. For example, Goldberg et al. (2020) find that rates of mangrove loss declined from 2000 to 2016. Such differences in estimates can be due to several factors, including lack of alignment in the time period assessed across studies, differences in methodology used for mapping, and differences in definitions.

64. Murray et al. (2022) report a 95 percent confidence interval of 0.33 to 0.68 Mha for this estimate.

65. If implemented inappropriately, reforestation, peatland rewetting, and mangrove restoration can generate adverse ecological effects. Planting alien species and/or monocultures, for example, threatens ecosystem integrity, while reforestation at higher latitudes, although beneficial for conserving biodiversity, provides few, if any, contributions to climate mitigation, as adding trees to these landscapes can alter the reflectivity of the planet's surface and produce a net warming effect (IPCC 2022b). Mangrove restoration projects, for example, often focused on large-scale planting of a single, sometimes nonnative species across unsuitable landscapes, and a survey of these initiatives across 11 countries in Southeast Asia found that few trees survived in the long term (Lee et al. 2019). In the Philippines, planting occurred across intact seagrass meadows, another important ecosystem for carbon storage (Fourqurean et al. 2012) and an inappropriate site for mangroves, while an overreliance on alien tree species spurred losses in ecosystem functioning across China's coastline (Lee et al. 2019). But when broader landscape restoration principles are applied (e.g., by focusing on restoring entire landscapes, recovering ecological integrity, delivering multiple benefits, etc.), these harmful impacts can often be prevented. For example, reestablishing natural hydrological regimes across mangrove forests is often more successful in restoring these coastal ecosystems than planting saplings, alone (Lewis 2001, 2005).

66. Although these targets fall below those set by the Bonn Challenge and the New York Declaration on Forests (350 Mha by 2030), they focus solely on reforestation, while both international commitments include pledges to plant trees across a broader range of land uses, such as agroforestry systems, and to restore a broader range of degraded ecosystems. See Jaeger et al. (2023) for more information on how these targets were established.

67. Tree cover gain is defined as the establishment or recovery of tree cover (i.e., woody vegetation with a height of greater than or equal to five meters) by the year 2020 in areas that did not have tree cover in the year 2000 (Potapov et al. 2022a). See Jaeger et al. (2023) for more information.

68. National contributions to this global reforestation target were derived from country-level estimates of cost-effective mitigation potential for this wedge from Roe et al. (2021) and, therefore, do not account for equity considerations. Global reforestation targets do not exceed the area associated with Griscom et al.'s (2017) global "maximum additional mitigation potential" for reforestation (678 Mha), which is a technical estimate of mitigation potential constrained by social and environmental safeguards. But downscaled, country-level mitigation potentials estimated by Roe et al. (2021) do not explicitly account for these same safeguards.

69. This report includes a more ambitious peatland restoration target than Roe et al. (2021) because some studies (e.g., Leifeld et al. 2019; Kreyling et al. 2021) argue that restoring nearly all degraded peatlands by around midcentury will be required to limit warming to 1.5°C or below, as emissions from drained peatlands may otherwise consume a large share of the global carbon budget associated with this temperature limit. However, as the IPCC (2022b) notes, restoring all degraded peatlands may not be possible (e.g., those upon which cities have been constructed, those subject to saltwater intrusion, or those already converted into plantation forests). While it remains to be determined with certainty what percentage can be feasibly rehabilitated, particularly at costs of up to \$100/tCO_2e (as noted in Griscom et al. 2017, the marginal abatement cost literature lacks a precise understanding of the complex, geographically variable costs and benefits associated with peatland restoration and, therefore, estimates of cost-effective peatland restoration vary), several reports find that restoring roughly 50 percent of degraded peatlands is needed to help deliver AFOLU's contribution to limiting global temperature rise to 1.5°C (e.g., Searchinger et al. 2019; Roe et al. 2019). We followed these studies and set a more ambitious target than Roe et al. (2021). Our 2050 target, then, involves restoring nearly half of degraded peatlands (recently estimated at 46 Mha by Humpenöder et al. 2020 to 57 Mha by UNEP 2022b) by midcentury. This target, then, represents an important starting point rather than a definitive goal for policymakers.

70. Rewetted peatlands emit more methane than intact peatlands, but net GHG emissions from these rewetted peatlands, on aggregate, are lower than GHG emissions from drained peatlands (Humpenöder et al. 2020; Günther et al. 2020).

71. National contributions to this global peatland restoration target were derived from country-level estimates of cost-effective mitigation potential for this wedge from Roe et al. (2021) and, therefore, do not account for equity considerations. Global peatland restoration targets do not exceed the area associated with Griscom et al. (2017)'s global "maximum additional mitigation potential" for peatland restoration (46 Mha), which is a technical estimate of mitigation potential constrained by social and environmental safeguards. But downscaled, country-level mitigation potentials estimated by Roe et al. (2021) do not explicitly account for these same safeguards.

72. This target is from Roe et al. (2021), who derive their estimates from Griscom et al. (2020). In measuring progress toward this 2030 target, we focus solely on mitigation outcomes directly attributed to human activities (Murray et al. 2022) and exclude gains in mangrove forest area that occur from inland migration, a natural, adaptive response that this ecosystem has to relative sea level rise (Schuerch et al. 2018). Also, the mitigation potential associated with this mangrove restoration target focuses solely on enhanced carbon sequestration (Griscom et al. 2020) and does not account for methane fluxes that occur naturally within these ecosystems and partially offset their carbon sequestration rates (Rosentreter et al. 2018, 2021).

73. Murray et al. (2022) report a 95 percent confidence interval of 0.09 to 0.30 Mha for this estimate.

74. Although the Food and Agriculture Organization of the United Nations collects and publishes national-level statistics on the area of managed forests every five years, global datasets that map managed forests are extremely limited. Similarly, no such datasets exist for grasslands.

75. Globally, recent evidence suggests that establishing protected areas can generate substantial carbon benefits (Duncanson et al. 2023). But findings from the literature on the effectiveness of specific protected areas vary significantly, with studies demonstrating both reductions in deforestation and increased deforestation across protected areas. Local factors, such as the quality of monitoring systems, access to finance, or poor enforcement, can impact protected areas' effectiveness and may account for some of these differences (Wolf et al. 2021; IPCC 2022b). This suggests that expanding protected areas may prove effective in some contexts but not others, and will likely be more effective in curbing deforestation when pursued within a broader portfolio of conservation policies.

76. This section uses FAOSTAT (2023) as its data source of agricultural production emissions, because these data are more detailed for this sector than those of Minx et al. (2021). We acknowledge the many limitations and uncertainties around measurement of agriculture and land-sector emissions, as well as agricultural land use, and targets should be refined in the future as the data continue to improve. To avoid double counting with other sections of this report, we do not count carbon dioxide from on-farm energy use, or carbon dioxide and nitrous oxide from drained organic soils and peatlands, in this section.

77. Several other emissions sources related to food and agriculture are covered elsewhere in this report. Carbon dioxide emissions from fossil fuel combustion occur during the production of agricultural inputs, in conjunction with on-farm energy use, and throughout the food system (e.g., food processing, transport, and packaging), but these fossil energy emissions are covered in the Power, Industry, and Transport sections. Similarly, carbon dioxide and other emissions from land-use change and drained organic soils (or peatlands) are covered in the Forests and Land section.

78. These subtargets by emissions source illustrate the relative importance of each activity to climate change mitigation, based on the modeling conducted by Searchinger et al. (2019) that underlies most of the targets in this section.

79. Food production provides people not only calories but also many other nutrients (e.g., proteins, vitamins, fiber). There is no one perfect normalization factor for this GHG intensity metric. For example, because sugars and processed grains are very GHG-efficient, the world could improve performance on this metric while worsening nutrition. This metric is used because data on production and consumption of calories are available in FAOSTAT (2023) for all countries. This metric should be improved while ensuring healthy diets for all. This indicator includes kilocalories of both plant- and animal-based foods in the global food supply, as tracked by FAOSTAT.

80. FAO crop yields are expressed in terms of fresh weight, unless otherwise specified within the database. Yields trends may be distorted by crops with high moisture content.

81. Food loss that occurs on farms (e.g., unharvested produce) is typically excluded from food loss and waste inventories, including those reported above, due to measurement challenges as well as underlying differences in the nature of the data (Hanson et al. 2017). That said, a recent report drew attention to the fact that preharvest food losses represent a significant additional source of emissions that could be measured and reduced moving forward (WWF-UK 2021).

82. This diet shift does not apply to populations within the Americas, Europe, and Oceania that already consume less than 60 kcal/capita/day, have micronutrient deficiencies, and/or do not have access to affordable and healthy alternatives to ruminant meat. FAOSTAT's definition of Oceania includes Australia, New Zealand, Melanesia, Micronesia, and Polynesia.

83. In this section, consumption data are given in availability, which is defined in FAO's Food Balance Sheets (FAOSTAT 2023) as the per capita amount of ruminant meat available at the retail level and is a proxy for consumption.

84. This diet shift does not apply to populations within the Americas, Europe, and Oceania that already consume less than 60 kcal/capita/day, have micronutrient deficiencies, and/or do not have access to affordable and healthy alternatives to ruminant meat. FAOSTAT's definition of Oceania includes Australia, New Zealand, Melanesia, Micronesia, and Polynesia.

85. This equivalent is based on a 100-gram serving of 80 percent lean beef that contains 248 kilocalories (USDA 2019). Following Searchinger et al. (2019), we assume actual consumption is 87 percent of retail-level food availability.

86. Different members use different base years due to data constraints

87. We focus on carbon dioxide removal rather than greenhouse gas removal as many methods for removing CO_2 from the atmosphere are in development, demonstration, and early commercial stages of growth, while removal of non-CO_2 gases such as methane is much more nascent (e.g., as proposed by Jackson et al. 2021); and because carbon dioxide has a longer lifetime than methane and exists at higher concentrations in the atmosphere.

88. Which emissions are considered "hard-to-abate" and appropriate to be counterbalanced by carbon removal is not clear and opinions differ. What counts as "hard-to-abate" depends on the cost and feasibility of deep decarbonization across all sectors as well as on political choices, such as levels of demand for certain emissions-intensive activities.

89. Point-source capture is defined as an emissions-reduction approach rather than carbon removal since it prevents emissions from entering the atmosphere.

90. What is considered durable or permanent sequestration is defined differently by different groups. Some governments and companies have suggested that storage over timescales from 10 years (Nori n.d.) to 100 years (Weiss 2022) could be considered as "permanent," but this is not consistent with the carbon cycle. From a scientific perspective, carbon would need to be stored over more than 1,000 years in order to fully compensate for the warming effect of the equivalent amount of CO2 emissions. Where the threshold for permanence is set will determine which technologies and approaches meet the definition of permanent CDR.

91. This is a gross number and does not factor in life-cycle emissions associated with ethanol combustion; factoring in these emissions would lower the net removal.

92. While still a draft proposal, the CRCF has been criticized for how it defines carbon removal and addresses questions of permanence. There are also questions around how it would interact with existing policy (CATF 2022a; Harvey 2022; Stoefs 2022) that should be addressed in ongoing conversations and finalization.

93. There is substantial debate about what should and should not be counted as climate finance, both in terms of sectors and types of financial flows. For the purposes of this section, we use the operational definition of climate finance from the UNFCCC's Standing Committee on Finance, which has also been used by the IPCC: "Climate finance aims at reducing emissions, and enhancing sinks of greenhouse gases and aims at reducing vulnerability of, and maintaining and increasing the resilience of, human and ecological systems to negative climate change impacts" (SCF 2014; IPCC 2022b).

94. A number of gaps exist in the climate finance tracking data, and Climate Policy Initiative (CPI), which provides the most comprehensive assessment of global climate finance flows, takes a conservative approach to collecting and reporting data. CPI makes efforts to avoid double-counting by excluding secondary market transactions such as trading on financial markets, because they do not represent new investment but rather exchange of money for existing assets; R&D and investment in manufacturing, since these costs are factored into financing for projects that ultimately deploy technologies; revenue support mechanisms such as feed-in tariffs and other public subsidies, since they are designed to pay back project investment costs; financing for fossil fuels; and data where they are unreliable, such as private sector energy efficiency investment (CPI 2021).

95. It is important to note that while international public climate finance flows are well tracked, comprehensive data on domestic public climate finance are available only for some countries (Naran et al. 2022), so total public climate finance may be higher than is currently tracked.

96. Significant data gaps exist for private climate finance tracking datasets, so actual climate-related finance flows may be higher (CPI 2021). This is part of why better disclosure, as covered in Indicator 4, is important.

97. Total climate finance from developed to developing countries, including export credits and mobilized private finance, was $83.3 billion in 2020 (OECD 2022a).

98. Note that this is different, and lower, than the ratio of total clean energy investment to fossil fuel investment, which also includes investments in energy efficiency and other end-use investments. The ratio of total clean energy to fossil fuel investment was 1.7:1 in 2023 (IEA 2023m). While investments in efficiency and electrifying end use are important, this indicator focuses on energy supply because end-use investments can be neutral to fuel source.

99. Disclosure requirements are not uniform among countries and apply to different or select types of firms (e.g., financial institutions or publicly traded firms) with diverse implementation timelines. We consider jurisdictions that implemented any form of mandatory requirement during the year it was approved, even if the requirement enters into force in phases with different timelines. Governments will need to expand the coverage of regulatory disclosure rules to all types of firms and sectors to achieve comprehensive measurement and disclosure of climate risks.

100.The IPCC's Sixth Assessment Report estimates the marginal abatement cost of carbon for pathways that limit warming to 1.5°C with no or limited overshoot as \$220/tCO$_2$ with an interquartile range of \$170–\$290/tCO$_2$ in 2030, and \$630/tCO$_2$ with an interquartile range of \$430–\$990/tCO$_2$ in 2050 (IPCC 2022b).

101. Production subsidies benefit the producers of fossil fuels, such as entities involved in exploration and extraction, bulk transportation and storage, and refining and processing. Consumption subsidies benefit consumers of fossil fuels, at the point at which they are combusted or used as end-use products, such as power and heat generation; industrial processes; use in transportation; and in primary industries such as agricultural fertilizer and plastic production (OECD and IISD 2023).

102.The IEA's (2021a) definition of clean energy includes renewables, nuclear, battery storage, energy efficiency and electrification, low-carbon fuels, and carbon capture, utilization, and storage.

103. The Greenhouse Gas Protocol classifies Scope 3 GHG emissions as indirect emissions that occur in a company's value chain.

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MAPS

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About Systems Change Lab

Systems Change Lab aims to drive change at the pace and scale needed to tackle some of the world's greatest challenges: limiting global warming to 1.5 degrees C, halting biodiversity loss and building a just and equitable economy. Convened by World Resources Institute and the Bezos Earth Fund, Systems Change Lab supports the UN Climate Change High-Level Champions and works with key partners and funders including Climate Action Tracker (a project of Climate Analytics and NewClimate Institute), ClimateWorks Foundation, Global Environment Facility, Just Climate, Mission Possible Partnership, Systemiq, University of Exeter and the University of Tokyo's Center for Global Commons, among others. Systems Change Lab is a component of the Global Commons Alliance.

About Systems Change Lab's Partners for this Report

Bezos Earth Fund

The Bezos Earth Fund is transforming the fight against climate change with the largest ever philanthropic commitment to climate and nature protection. We're investing $10 billion in this decisive decade to protect nature and drive systems-level change, creating a just transition to a low-carbon economy. By providing funding and expertise, we partner with organizations to accelerate innovation, break down barriers to success and create a more equitable and sustainable world. Join us in our mission to create a world where people prosper in harmony with nature.

Climate Action Tracker

The Climate Action Tracker (CAT) is an independent research project that tracks government climate action and measures it against the globally agreed Paris Agreement goal of limiting warming to 1.5˚C. A collaboration of two organizations, Climate Analytics and NewClimate Institute, the CAT has been providing this independent analysis to policymakers since 2009.

Climate Analytics

Climate Analytics is a global climate science and policy institute engaged around the world in driving and supporting climate action aligned to the 1.5°C warming limit. It has offices in Africa, Australia and the Pacific, the Caribbean, North America and South Asia.

ClimateWorks Foundation

ClimateWorks Foundation is a global platform for philanthropy to innovate and scale high-impact climate solutions that benefit people and the planet. We deliver global programs and services that equip philanthropy with the knowledge, networks, and solutions to drive climate progress for a more sustainable and equitable future. Since 2008, ClimateWorks has granted over $1.7 billion to more than 750 grantees in over 50 countries.

NewClimate Institute

NewClimate Institute is a non-profit think tank supporting implementation of action against climate change in the context of sustainable development around the world. NewClimate Institute connects up-to-date research with real world decision-making processes with a focus on international climate negotiations, national and sectoral climate action and corporate climate commitments.

United Nations Climate Change High-Level Champions

The United Nations Climate Change High-Level Champions for COP27 and COP28 – Mahmoud Mohieldin and Razan Al Mubarak – drive real world momentum into the UN Climate Change negotiations. They do this by mobilizing climate action amongst non-State actors (companies, cities, regions, financial, educational and healthcare institutions) to achieve the goals of the Paris Agreement, in close collaboration with the UNFCCC, the Marrakech Partnership and the COP Presidencies.

World Resources Institute

World Resources Institute is a global research organization that turns big ideas into action at the nexus of environment, economic opportunity, and human well-being.

Our Challenge: Natural resources are at the foundation of economic opportunity and human well-being. But today, we are depleting Earth's resources at rates that are not sustainable, endangering economies and people's lives. People depend on clean water, fertile land, healthy forests, and a stable climate. Livable cities and clean energy are essential for a sustainable planet. We must address these urgent, global challenges this decade.

Our Vision: We envision an equitable and prosperous planet driven by the wise management of natural resources. We aspire to create a world where the actions of government, business, and communities combine to eliminate poverty and sustain the natural environment for all people.

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