SYSTEMS CHANGE LAB

STATE OF CLIMATE ACTION 2022

BEZOS EARTH FUND

Climate Action Tracker

CLIMATE ANALYTICS

climateworks FOUNDATION

NEW CLIMATE INSTITUTE

RACE TO ZERO

RACE TO RESILIENCE

WORLD RESOURCES INSTITUTE

About the Authors

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

Chapter Authors:

- **Methodology:** Joel Jaeger, Sophie Boehm, Clea Schumer, and Judit Hecke
- **Power:** Aman Majid, Ryan Wilson, Andreas Geiges, and Stephen Naimoli
- **Buildings:** Louise Jeffery
- **Industry:** Anna Nilsson and Neelam Singh
- **Transport:** Stephen Naimoli, Sebastian Castellanos, and Ryan Wilson
- **Forests and Land:** Sophie Boehm and Michelle Sims
- **Food and Agriculture:** Emily Cassidy and Richard Waite
- **Technological Carbon Removal:** Katie Lebling
- **Finance:** Joe Thwaites and Anderson Lee

SUGGESTED CITATION

Boehm, S., L. Jeffery, K. Levin, J. Hecke, C. Schumer, C. Fyson, A. Majid, J. Jaeger, A. Nilsson, S. Naimoli, J. Thwaites, E. Cassidy, K. Lebling, M. Sims, R. Waite, R. Wilson, S. Castellanos, N. Singh, A. Lee, and A. Geiges. 2022. *State of Climate Action 2022*. Berlin and Cologne, Germany, San Francisco, CA, and Washington, DC: Bezos Earth Fund, Climate Action Tracker, Climate Analytics, ClimateWorks Foundation, NewClimate Institute, the United Nations Climate Change High-Level Champions, and World Resources Institute. https://doi.org/10.46830/wrirpt.22.00028.

Version 1.2. October 2022.

DESIGN

Studio Red Design (Alston Taggart and Kevin Sample) and Carni Klirs

Acknowledgments

This report was made possible by the generous financial contributions and thought leadership from Bezos Earth Fund, the Center for Global Commons, ClimateWorks Foundation, the Global Commons Alliance, the Global Environment Facility, and Just Climate.

Published under Systems Change Lab, this report is a joint effort between Bezos Earth Fund, Climate Action Tracker, Climate Analytics, ClimateWorks Foundation, NewClimate Institute, the United Nations Climate Change High-Level Champions, and World Resources Institute.

The authors would like to acknowledge the following for their guidance, critical reviews, and research support:

- The report benefited not only from ClimateWorks Foundation's financial support but also from the work of the Foundation's Global Intelligence team, particularly Dan Plechaty and Surabi Menon, who played pivotal roles in conceiving the idea for the analysis and providing technical support throughout the research, writing, and peer review process.
- Bill Hare and Deborah Ramalope from Climate Analytics, Niklas Höhne, Hanna Fekete, and Takeshi Kuramochi from NewClimate Institute, and Laura Malaguzzi Valeri, David Waskow, Rhys Gerholdt, Rachel Jetel, and Pankaj Bhatia from WRI all provided valuable conceptual inputs, review, and strategic guidance.
- The United Nations Climate Change High-Level Champions, Nigel Topping and Mahmoud Mohieldin, provided critical thought leadership and insights, as did several members of their team, including Alex Joss, Frances Way, Simon Sharpe, Jen Austin, and Matthew Phillips.
- Yuke Kirana, Markus Hagemann, Leonardo Nascimento, Amandeep Gill-Lang, Alissa Huntington, Thet Hein Tun, Adam Davidson, and Joël Beuerle made substantive contributions to the report.

We would also like to thank the report's reviewers who have shared their time, expertise, and insights: Ake Rosenqvist, Albena Ivanova, Alex Perera, Angela Anderson, Angie Farrag-Thibault, Anna Stratton, Avery Cohn, Avery Driscoll, Axum Teferra, Bella Tonkonogy, Ben Welle, Bex Porter, Bharath Jairaj, Caitlin Smith, Claudia Adriazola-Steil, Clay Nesler, D. Taylor Reich, Dan Lashof, Danielle Deane-Ryan, Dave Jones, David Gibbs, Debbie Weyl, Dede Sulaeman, Eva Kinnebrew, Frances Seymour, Frances Wang, Francesco N. Tubiello, Fred Stolle, Fridolin Krausmann, Gaia Larsen, Giulia Laganà, Haldane Dodd, Hanna Fekete, Hans Joosten, Harald Friedl, Harsh Vijay Singh, Hidayah Hamzah, Ingrid Schulte, Jacob Teter, Jen Austin, Jinlei Feng, John Feldmann, Jonah Busch, Jonathan Baines, José Segundo López, Karl Hausker, Katharine Palmer, Katia Simeonova, Katie O'Gara, Katie Ross, Katrina McLaughlin, Kelly Carlin, Kevin Kennedy, Kyoung Choi, Laëtitia de Villepin, Laia Barbarà, Lammert Hilarides, Leon Clarke, Lihuan Zhou, Lindsey Sloat, Liqing Peng, Lola Fatoyinbo, Maria Brockhaus, Maria Nuutinen, Marion Hsieh, Marion Vieweg, Marta Torres, Matt Daggett, Matt Ives, Michael Wolosin, Mikaela Weisse, Mohamed Hegazy, Nancy Harris, Nathan Mueller, Nik

Acknowledgments (CONTINUED)

Pavlenko, Nikola Medimorec, Nora Steurer, Paige Langer, Pete Bunting, Peter Veit, Prashanth Gururaja, Rachel Fakhry, Radhika Lalit, Ray Wills, Rebecca Fisher, Robin Chase, Seth Monteith, Sibyl Steuwer, Simon Nicholson, Stephanie Roe, Surabi Menon, Susan Cook-Patton, Takeshi Kuramochi, Teresa Kennedy, Todd Litman, Tom Quinn, Tristan Smith, Victoria Burrows, Zachary Byrum, Zarrar Khan, and Zhuohui Huang. While the contributions from reviewers are greatly appreciated, the views presented in this report are those of the authors alone.

The authors are grateful to WRI colleagues for their support in the production of the report, including administrative assistance, editing, graphic design, and layout: Romain Warnault, Emilia Suarez, Renee Pineda, Emily Matthews, Mary Levine, Shannon Collins, Lucie Quinn, and Joshua Lee.

We received communications and outreach support from Irene Berman-Vaporis, Rhys Gerholdt, Matthew Phillips, Victoria Fischdick, Cindy Baxter, Stacie Paxton Cobos, Rocío Lower, Sarah Parsons, Brynne Wilcox, Alison Cinnamond, Mollie Freeman, Tim Lau, and Jennifer Rigney.

WRI is also pleased to acknowledge the institutional strategic partners, who provide core funding to the Institute: the Netherlands Ministry of Foreign Affairs, the Royal Danish Ministry of Foreign Affairs, and the Swedish International Development Cooperation Agency.

Contents

Foreword

Countries around the world are set to gather in Sharm el-Sheik, Egypt for COP27, seven years after the historic Paris Agreement. In many ways, we enter this COP much better equipped to address the climate crisis than ever before. Recent growth in electric vehicle sales has increased so rapidly that they will soon outpace sales of passenger cars with internal combustion engines—by one estimate, sales of these fossil fuel–powered cars already peaked globally in 2017. This year is also shaping up to be another record-breaking year for renewables, with additional renewable electricity capacity expected to increase over 8 percent in 2022. And largely driven by progress in China, the global share of battery electric and fuel cell electric vehicles in bus sales grew from 2 percent in 2013 to 44 percent in 2021— an increase of over 20 times in under a decade. These advances give us confidence that we can act decisively—and with results.

Yet during the seven years following the adoption of the Paris Agreement, GHG emissions have continued to climb. Climate shocks are erasing hard-won development gains, from widespread floods across Pakistan to crop-withering droughts in East Africa to extreme storms pummeling coastlines around the world. At the same time, COVID-19 dealt the largest blow to extreme poverty-reduction efforts in the past three decades, and the majority of recovery efforts have failed to prioritize a net-zero future. Russia's invasion of Ukraine has led to devastating loss of life, threatened energy security, and triggered cascading impacts to food security that has forced millions into famine. Together, these crises are imperiling our fragile system of global cooperation at exactly the time when it is most needed.

Keeping the Paris Agreement's goal to limit global warming to 1.5°C within reach will require an enormous acceleration of transformations across all systems this decade. As a report card on global climate action, this new, latest installment of the *State of Climate Action* from Systems Change Lab translates these systemwide transformations into 40 indicators of progress with 2030 and 2050 targets to highlight where—and by how much—progress must accelerate to avoid increasingly dangerous climate impacts.

Its findings are sobering. While we are beginning to see some bright spots, none of the 40 indicators of progress spanning the highest-emitting systems, carbon removal, and climate finance are on track to achieve 1.5°C-aligned targets for 2030. To avoid the increasingly dangerous, and in some cases, irreversible climate impacts, efforts to phase out coal generation need to accelerate six-fold, equivalent to retiring 925 average-sized coal plants each year through 2030. Declines in annual deforestation rates need to occur 2.5 times faster, equivalent to stopping deforestation across an area roughly the size of all the arable land in Switzerland every year this decade. And shifting to healthier, more sustainable diets must occur five times faster by reducing per capita consumption of ruminant meat to roughly two burgers per week across the Americas, Europe, and Oceania. Recent increases in total global climate finance, which facilitates these transformations, need to grow over 10 times faster—by roughly $460 billion every year this decade. This is well below the $726 billion invested in fossil fuels globally in 2020 alone.

There is no silver bullet to transforming every system—from how we grow our food to how we power our lives and transport goods to how we build our cities. Delivering these transitions on time will require leaders everywhere to employ every tool at their disposal, including economic incentives, regulations and laws, strong institutions, shifts in behavior, innovations, and unwavering, courageous leadership.

A year ago, more than 100,000 people marched through the streets of Glasgow, Scotland for climate justice, and since then, more than 200 protests have occurred around the world, with people from all corners of society calling upon their leaders to step up climate action. The increasing public support for climate action creates a window of opportunity to act, just at a time when the path to limiting warming to 1.5°C is increasingly narrowing. How we choose to proceed at this crossroads will determine the well-being of today's younger generations and all those to come.

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

Helen Mountford
President and CEO, ClimateWorks Foundation

Andrew Steer
President and CEO, Bezos Earth Fund

Nigel Topping
United Nations Climate Change High-Level Champion

Executive Summary

Our climate is already changing dramatically, with 1.1°C of global average warming since the preindustrial era. This past year, an unbearable, deadly heatwave scorched India and Pakistan, with the highest temperatures ever recorded (Coleman 2022). Unprecedented heat also reached Antarctica, where temperatures were roughly 39°C above normal (Samenow and Patel 2022), and during this period of abnormally warm weather, the first ice shelf in East Antarctica collapsed since satellites started monitoring the region nearly half a century ago (Fountain 2022). In the United States, a megadrought has gripped southwestern states for two decades, with 2021 seeing such extreme dryness that it has now been classified as the worst drought in 1,200 years (Harvey 2022). Drought, coupled with extreme heat, is also blanketing China, shutting down factories, crippling hydroelectric power, and driving up the use of coal (Bradsher and Dong 2022). Elsewhere, heavy rainfall attributed to climate change has spurred severe flooding and landslides that are devastating communities in South Africa and Brazil (WWA 2022; Carrington 2022). In Pakistan, eight consecutive weeks of torrential monsoon rains triggered devastating floods that left one-third of the country underwater (Sands 2022; Shih et al. 2022). And off the coast of Australia, the Great Barrier Reef experienced its sixth mass bleaching event, which is particularly noteworthy because it occurred during a La Niña year that typically brings cooler temperatures and rain (Cave 2022).

At the same time, countries are grappling with numerous crises that risk stymying climate action. Nations are still rebuilding their economies from the recession triggered by the first wave of COVID-19, and many are largely missing the opportunity to focus spending on a green recovery, instead making investments today that will lock in decades' worth of high-carbon infrastructure (UNEP 2021c). Russia's invasion of Ukraine has triggered a rapid shift in decades-old patterns of geopolitics, threatening a reversal of global integration and hindering international cooperation. Nations around the world are rethinking their strategic approach to food, energy, and military security as this conflict disrupts supply chains and raises perceived threat levels. A short-term spike in fossil fuel investments looms large, given the abrupt nature of these supply disruptions, and these investments risk becoming stranded assets should the world accelerate mitigation efforts to achieve the Paris Agreement. Relatedly, inflation is also surging in many countries, with some seeing the highest levels in 40 years (Phillips 2022). The cascading effects of these crises are disproportionally impacting emerging economies and developing countries, given the limited resources to address them (United Nations 2022a, 2022b, 2022c). Across East Africa, for example, the confluence of consecutive severe droughts, rising food prices, disruptions in food imports arising from Russia's invasion of Ukraine, and regional conflicts have spurred dramatic increases in acute food insecurity (IGAD 2022).

Highlights

- Limiting global warming to 1.5°C requires transforming almost all systems, from how we power our economy and build our cities to how we feed a growing population and manage our land.
- But these transformations are not occurring nearly fast enough. This report assesses progress across 40 indicators of systems change and finds that none are on track to reach their 2030 targets.
- Change is heading in the right direction at a promising but insufficient speed for 6 indicators, and in the right direction but well below the required pace for 21. Change in another 5 indicators is heading in the wrong direction entirely, and data are insufficient to evaluate the remaining 8.
- Getting on track to achieve 2030 targets will require an enormous acceleration in effort. Unabated coal in electricity generation, for example, must be phased out six times faster than recent global rates. Improvements in cement production's carbon intensity must increase much more quickly—by a factor of more than 10. And reductions in the annual deforestation rate must accelerate 2.5 times faster.
- Although there are some signs of progress, the window to limit warming to 1.5°C is rapidly closing, with national 2030 climate commitments, even when fully implemented, leading to roughly 2.4°C to 2.8°C. To close this gap, this report identifies supportive measures that can advance action at the speed and scale required.
- The transformations ahead can bring tremendous benefits, but they will not be easy. Accelerating just transitions will require greater, more inclusive efforts, substantially more finance, and careful evaluations of impacts on people as change unfolds.

We have never had more information about the gravity of the climate emergency and its cascading impacts, or about what needs to be done to reduce these intensifying risks. Over the past year, the Intergovernmental Panel on Climate Change (IPCC), the International Energy Agency (IEA), and other scientific bodies have charted an increasingly narrow, yet still achievable way forward to achieving the Paris Agreement's 1.5°C temperature limit. And while there are multiple pathways for limiting global warming to 1.5°C, all share common features—for example, decarbonizing electricity, reducing and reversing forest, peatland, and coastal wetland loss, shifting to more sustainable modes of transport,

electrifying buildings and industry, using energy more efficiently, and removing previously emitted carbon dioxide from the atmosphere.

All remaining pathways to 1.5°C also require immediate and ambitious action—neither people nor the planet can afford to continue delaying climate action. Even if current 2030 climate pledges are fully implemented, scientists estimate that we will face warming of roughly 2.4°C to 2.8°C by the end of the century (IPCC 2022b; Climate Action Tracker 2021). This future represents an unrecognizable world of hardship in which some regions are no longer habitable, agricultural fields either dry up or are inundated with floodwaters, greater swaths of forests burn for longer, an increasing number of species face extinction, and rising seas swallow coastlines. In this world, climate impacts perpetuate injustice and inequity, with those who often have the fewest resources to adapt, namely historically marginalized communities, bearing the brunt of costs and impacts.

But we need not accept this future, and some decision-makers are beginning to wake up. An increasing number of leaders across government, the private sector, and civil society understand the urgent need to mitigate climate change, as well as the benefits of immediate action. Consequently, climate action is now becoming more mainstream across all aspects of the economy and society—from central banks and multilateral development institutions to mayors and ministers to companies and local community groups. Today, nearly 100 countries, contributing over 75 percent of global emissions, alongside roughly 7,500 companies and 1,100 cities, have announced a target to reach net-zero emissions. Managers of over US$130 trillion in assets have also committed to align their investment portfolios with the Paris Agreement's 1.5°C temperature limit. Some private sector leaders, specifically, see not only that climate impacts threaten their bottom lines but also the strategic opportunity in being a first mover in the emerging markets of a zero-carbon, resilient future. And they are responding to signals from policymakers who, by putting ambitious commitments and policies in place, are providing the clarity and confidence that financial institutions and companies need to act boldly. In turn, the actions of these nonstate actors indicate clear support for national governments to continue strengthening policies. But what is needed now, more than ever, is the translation of these efforts into real-world action that delivers the greenhouse gas (GHG) emissions reductions and carbon removal at the speed and scale required to limit warming to 1.5°C.

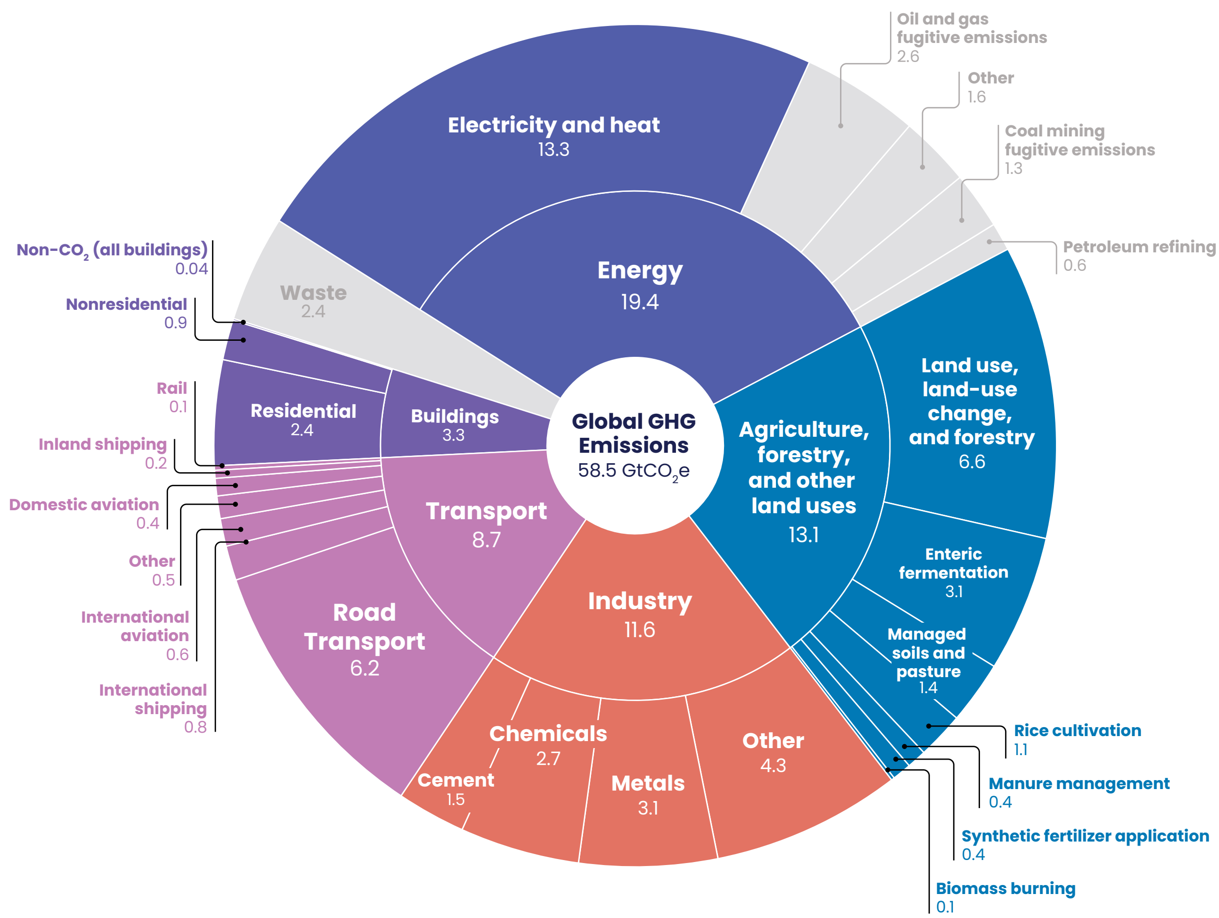
There are bright spots of action today that show us what is possible if we and our leaders dedicate ourselves fully to the required transformations. The share of renewables in electricity generation has increased from 20 percent in 1990 to 29 percent in 2020 (IEA 2021d), and renewables accounted for 82 percent of new capacity additions in 2020 (IRENA 2021a). Battery prices have fallen by 89 percent over the past decade and are expected to bring light-duty battery electric vehicles to price parity with their internal combustion engine counterparts in some major markets in the next five years (BNEF 2022a). Efforts to phase out the sales of fossil fuel–powered cars are simultaneously spreading, most recently with the European Union setting a phaseout date of 2035 (Abnett 2022). And the global share of zero-emission bus sales reached 44 percent in 2021 from 2 percent in 2013—an increase of over 20 times in under a decade, driven almost entirely by Chinese demand (BNEF 2022a). These encouraging examples did not happen on their own. They were nurtured by decision-makers (and those who influence them), with supportive policies and investments. While promising, momentum across some technologies and geographies will need to be significantly accelerated, as well as expanded across all systems, to keep 1.5°C in reach.

We need to manage the transitions in a just and equitable manner. Despite the tremendous benefits of a more sustainable future, the transitions required—from phasing out coal-fired power plants to changing agricultural practices—will create both opportunities and challenges, including exacerbating existing inequalities if implemented inappropriately. Measures must be put in place from the start that, among other objectives, ensure quality jobs and alternative livelihoods for those most affected, as well as broader economic responses, among them social safety nets, reskilling, economic diversification, and innovation. At the same time, the benefits and opportunities reaped from the transition must be shared equitably. Achieving these goals will require that all those impacted by these transitions have the information, power, and voice to shape decision-making processes.

About this report

Published under Systems Change Lab, this report is a joint effort of Bezos Earth Fund, Climate Action Tracker (an independent analytic group comprising Climate Analytics and NewClimate Institute), ClimateWorks Foundation, the United Nations Climate Change High-Level Champions, and World Resources Institute. It provides an overview of how we are collectively doing in addressing the climate crisis by accelerating the system-wide transformations across power, buildings, industry, transport, forests and land, and food and agriculture, as well as the immediate scale-up of carbon dioxide removal technologies and climate finance, that the IPCC finds are needed to limit global temperature rise to 1.5°C (IPCC 2022b). Taking stock of progress to date is critical for informing where best to focus our attention and change our future course of action. The report begins with a brief explanation of our methodology, including our selection of systems, targets, indicators, datasets, and enabling conditions, as well as our methods for assessing progress toward near-term targets (see our accompanying technical note, Schumer et al. 2022, for a more detailed explanation of these methods). It then assesses the pace

FIGURE ES-1 | Global GHG emissions by sector in 2019



Notes: CO_2 = carbon dioxide; GHG = greenhouse gas; $GtCO_2e$ = gigatonnes of carbon dioxide equivalent.
Source: Minx et al. (2022), described in Minx et al. (2021) and used in IPCC (2022b).

of action on mitigation to date in key sectors and compares it with where we need to go by 2030 and by 2050 to help limit global warming to 1.5°C. While a similar effort is warranted to evaluate the pace of adaptation action, this report's scope is limited to tracking progress on GHG emissions reductions and the removal of carbon from the atmosphere.

This report builds upon and updates previous assessments (Climate Action Tracker 2020c; Lebling et al. 2020; Boehm et al. 2021). It identifies 1.5°C-aligned targets and associated indicators for power, buildings, industry, transport, forests and land, and food and agriculture that the literature suggests are the best available to monitor sectoral climate mitigation pathways. Together, these sectors accounted for roughly 85 percent of net anthropogenic GHG emissions globally in 2019 (Figure ES-1). It also includes targets and indicators to track progress made in scaling up carbon dioxide removal technologies and finance, both of which will be needed to achieve the Paris Agreement's 1.5°C limit on temperature increase. We then assess progress by calculating a linear trendline based on the past five years of historical data (or 10 years for forests and land indicators) and comparing this trend to what's needed to reach 1.5°C-aligned near-term targets. Using these data, we calculated acceleration factors to quantify how much the pace of recent change needs to increase, and used these acceleration factors to classify indicators as on track, off track, well off track, or heading in the wrong direction entirely.

The report also determines the likelihood that future change in each indicator is likely to follow an S-curve, categorizing it as exponential change likely, exponential change possible, or exponential change unlikely. For the indicators that are exponential change likely, we determined whether to adjust the categorization of whether the shift is on track or not, based on the literature, current policy projections that consider nonlinear change, and expert consultations.

Finally, each section explores the barriers to more ambitious action, as well as a key set of factors that can enable transformational change across each system. While more research is needed to identify—and effectively track—these determinants of transformation, the report aims to support decision-makers in government, companies, investing firms, and funding institutions dedicated to accelerating climate action. A secondary audience is subject matter experts and civil society organizations who support these decision-makers in strengthening implementation of existing commitments and increasing ambition.

Key findings

Global GHG emissions today are higher than they were when more than 190 Parties adopted the Paris Agreement in 2015, with levels of carbon dioxide emissions already rebounding from their temporary drop at the start of the COVID-19 crisis. Recent efforts to reduce GHG emissions, as well as scale up carbon removal, are uneven across indicators in power, buildings, industry, transport, forests and land, food and agriculture, technological carbon removal, and finance (Figure ES-2). Thus, while numerous countries, cities, and companies have committed to step up mitigation efforts, much greater ambition and action is urgently needed if we are to meet the Paris Agreement's objective to pursue efforts to limit warming to 1.5°C (Table ES-1).

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

ON TRACK: Change is occurring at or above the pace required to achieve the 2030 targets

No indicators assessed exhibit a recent historical rate of change that is at or above the pace required to achieve their 2030 targets.

OFF TRACK: Change is heading in the right direction at a promising, but insufficient pace

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

WELL OFF TRACK: Change is heading in the right direction, but well below the required pace

For **21 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: Change is heading in the wrong direction, and a U-turn is needed

For **5 indicators**, the rate of change is heading in the wrong direction entirely.

Insufficient Data: Data are insufficient to assess the gap in action required for 2030

For **8 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)

TRAJECTORY OF CHANGE — ACCELERATION FACTOR[a]

>10x Exponential Unlikely

Because they track activities or practices that are not closely related to technology adoption, these indicators are unlikely to experience rapid, non-linear change. Our assessment relies on acceleration factors—calculations of how much the historical linear rate of change must accelerate to achieve the 2030 target.

2x Exponential Likely

Because they track technology adoption directly, these indicators are most likely to follow an S-curve. Our assessment relies on acceleration factors, but in some cases we adjust the status based on the literature or expert judgment.

5x Exponential Possible

Because they indirectly or partially track technology adoption, these indicators could possibly experience an unknown form of rapid, non-linear change. Our assessment relies on acceleration factors, but change may occur faster than expected.

Note: We use "exponential" because it is a commonly known term for non-linear change, but not all non-linear change is exponential.

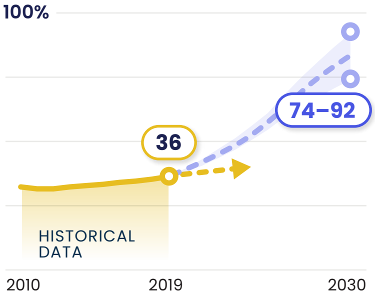
ON TRACK: Change is occurring at or above the pace required to achieve the 2030 targets

None

OFF TRACK: Change is heading in the right direction at a promising, but insufficient pace

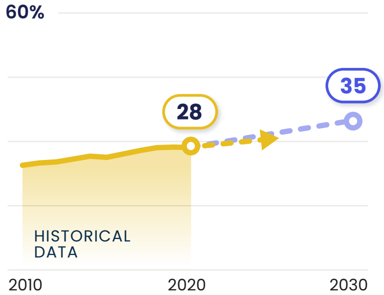
POWER 6x[b]

Increase the share of zero-carbon sources in electricity generation to 74–92%



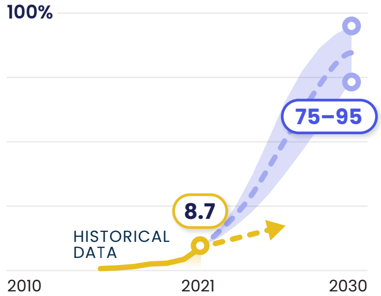
INDUSTRY 1.7x

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



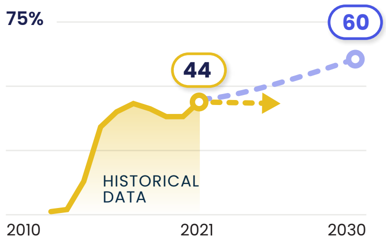
TRANSPORT 5x[b]

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



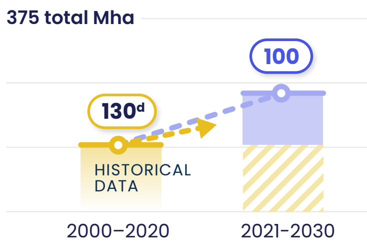
TRANSPORT >10x[b]

Boost the share of BEVs and FCEVs to 60% of annual global bus sales



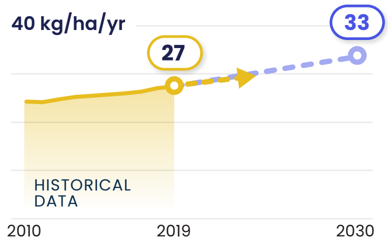
FOREST AND LAND 1.5x[c]

Reforest 100 Mha



FOOD AND AGRICULTURE 1.3x

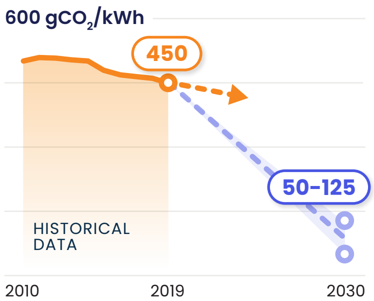
Increase ruminant meat productivity per hectare by 27%, relative to 2017



WELL OFF TRACK: Change is heading in the right direction, but well below the required pace

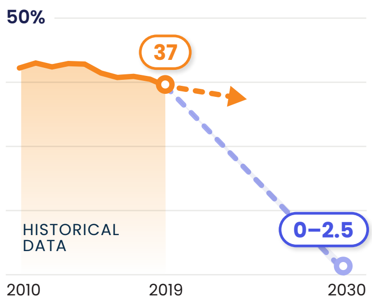
POWER 5x

Reduce the carbon intensity of electricity generation to 50–125 gCO_2/kWh



POWER 6x

Reduce the share of unabated coal in electricity generation to 0–2.5%



BUILDINGS 5x Commercial 7x Residential

Decrease the energy intensity of operations by 20–30% in residential buildings and by 10–30% in commercial buildings, relative to 2015[e,f]

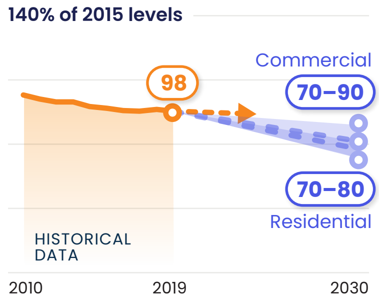


FIGURE ES-2 | Assessment of global progress toward 2030 targets (continued)

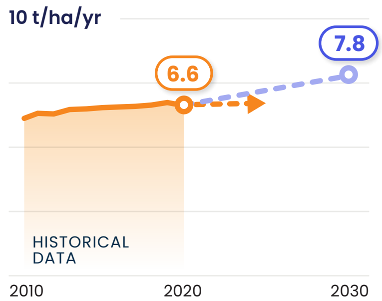
WELL OFF TRACK: Change is heading in the right direction, but well below the required pace

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

WELL OFF TRACK: Change is heading in the right direction, but well below the required pace

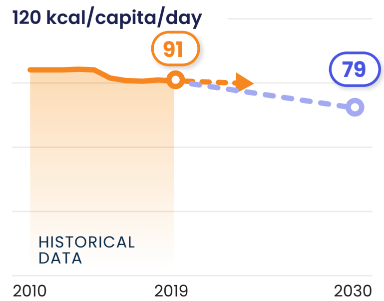
FOOD AND AGRICULTURE 6x

Increase crop yields by 18%, relative to 2017



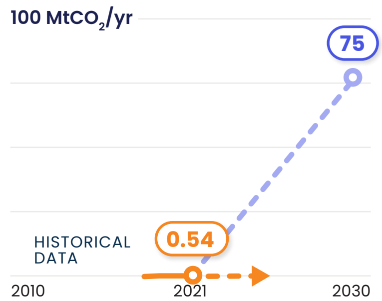
FOOD AND AGRICULTURE 5x

Reduce daily per capita ruminant meat consumption to 79 kilocalories across high-consuming regions[i]



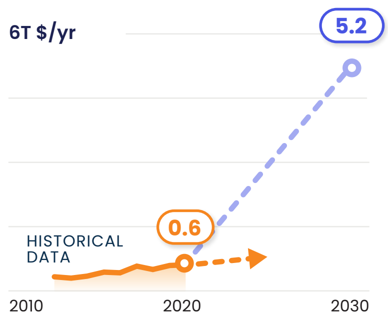
TECHNOLOGICAL CARBON REMOVAL >10x[j]

Increase annual technological carbon removal rates to 75 $MtCO_2$ /yr



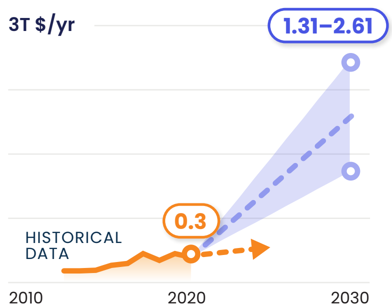
FINANCE >10x

Increase global climate finance flows (public and private, domestic and international) to US$5.2 trillion per year



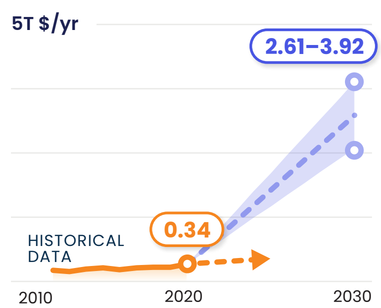
FINANCE >10x

Increase global public climate finance flows (domestic and international) to US$1.31–2.61 trillion per year



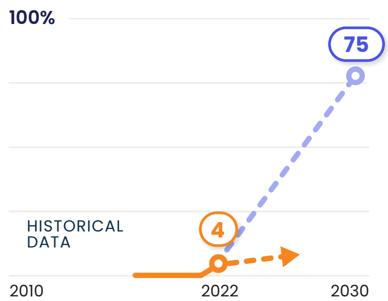
FINANCE >10x

Increase global private climate finance flows (domestic and international) to $2.61–3.92 trillion per year



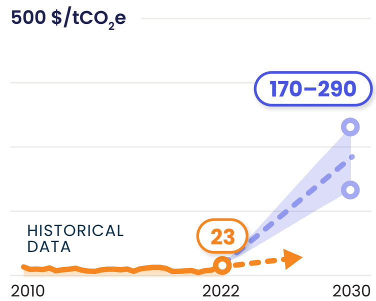
FINANCE >10x

Mandate alignment with the TCFD's recommendations on climate risk reporting in jurisdictions representing 75% of global emissions



FINANCE 8x

Raise the median carbon price in jurisdictions with pricing systems in place to $170–$290/tCO_2e[k]



FINANCE 5x

Phase out public financing for fossil fuels, including subsidies, with G7 countries and international financial institutions achieving this by 2025

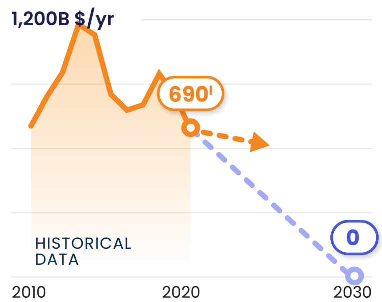
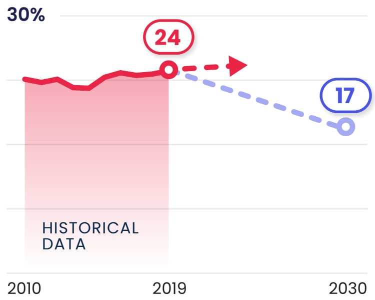


FIGURE ES-2 | Assessment of global progress toward 2030 targets (continued)

WRONG DIRECTION: Change is heading in the wrong direction, and a U-turn is needed

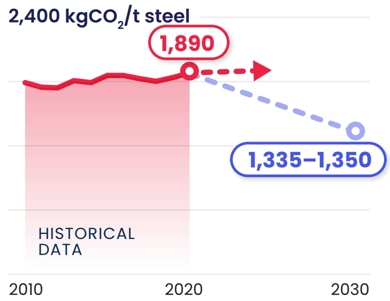
POWER N/A

Reduce the share of unabated fossil gas in electricity generation to 17%



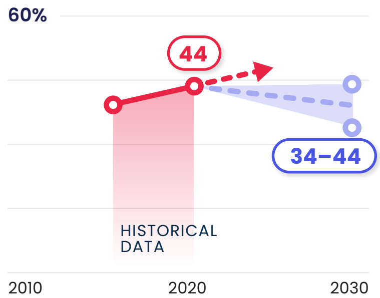
INDUSTRY N/A

Reduce the carbon intensity of global steel production to 1,335–1,350 kgCO2/t of steel



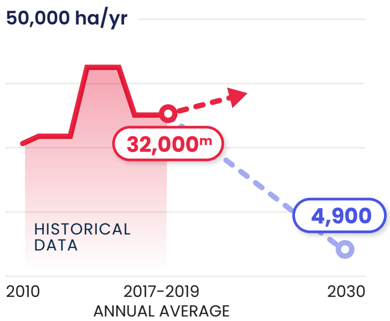
TRANSPORT N/A[g]

Reduce the percentage of kilometers traveled by passenger cars to 4–14 percent below business-as-usual levels



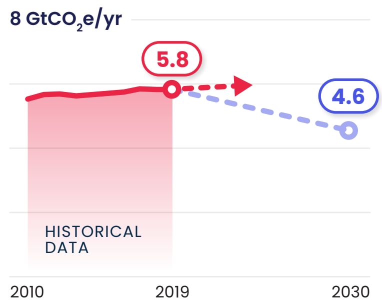
FORESTS AND LAND N/A[c]

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



FOOD AND AGRICULTURE N/A

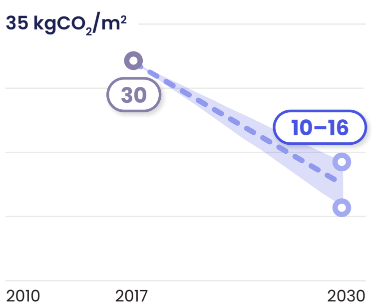
Reduce global GHG emissions from agricultural production by 22%, relative to 2017



Insufficient Data: Data are insufficient to assess the gap in action required for 2030

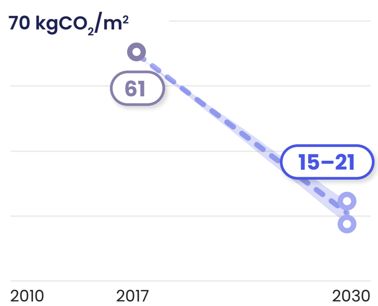
BUILDINGS Ins. data

Reduce the carbon intensity of operations in select regions by 45-65% in residential buildings relative to 2015



BUILDINGS Ins. data

Reduce the carbon intensity of operations in select regions by 65-75% in commercial buildings, relative to 2015



BUILDINGS Ins. data

Increase the annual global deep retrofitting rate of buildings to 2.5–3.5%

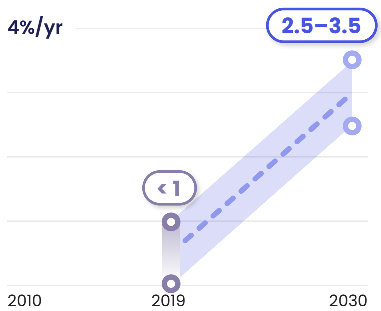
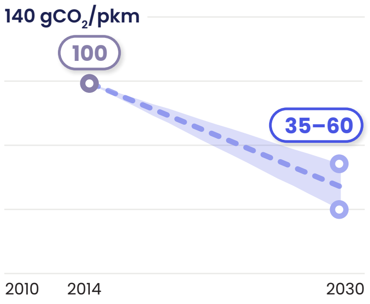


FIGURE ES-2 | Assessment of global progress toward 2030 targets (continued)

Insufficient Data: Data are insufficient to assess the gap in action required for 2030

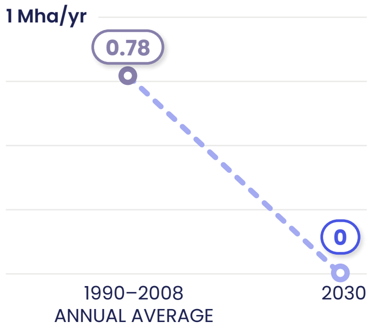
TRANSPORT Ins. data

Reduce the carbon intensity of land-based passenger transport to 35–60 gCO_2/pkm



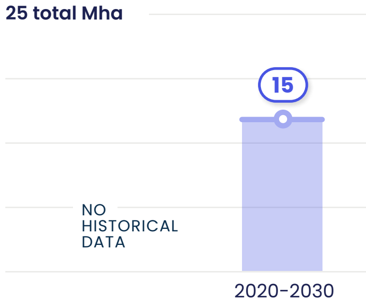
FORESTS AND LAND Ins. data[c]

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



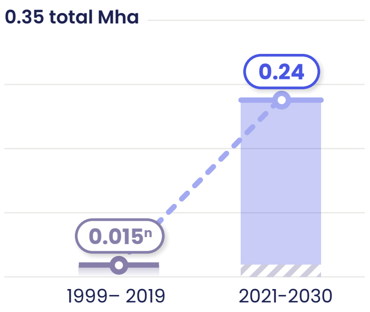
FORESTS AND LAND Ins. data[c]

Restore 15 Mha of degraded peatlands



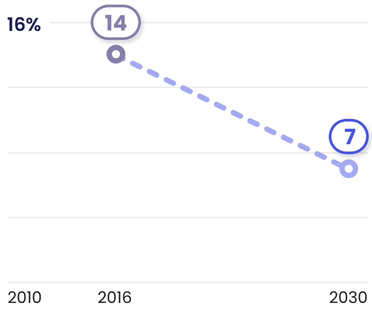
FORESTS AND LAND Ins. data[c]

Restore 0.24 Mha of mangrove forests



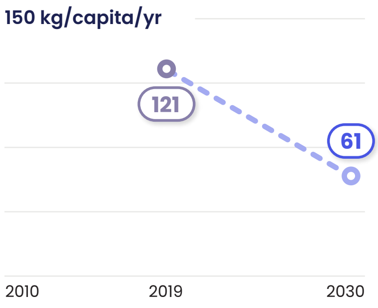
FOOD AND AGRICULTURE Ins. data

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



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; G7 = group of seven; gCO_2/kWh = grams of carbon dioxide per kilowatt-hour; gCO_2/pkm = grams of carbon dioxide per passenger kilometer; GHG = greenhouse gas; $GtCO_2e/yr$ = gigatonnes of carbon dioxide equivalent per year; ha/yr = hectares per year; kcal/capita/day = kilocalories per capita per day; kg/capita/yr = kilograms per capita per year; kg/ha/yr = kilograms per hectare per year; $kgCO_2/m^2$ = kilograms of carbon dioxide per square meter; $kgCO_2/t$ = kilograms of carbon dioxide per tonne; km = kilometer; LDV = light-duty vehicle; Mha = million hectares; Mha/yr = million hectares per year; MHDV = medium- and heavy-duty vehicles; Mt = million tonnes; $MtCO_2/yr$ = million tonnes of carbon dioxide per year; SAF = sustainable aviation fuel; TCFD = Task Force on Climate-Related Financial Disclosures; t/ha/yr = tonnes per hectare per year; US$/$tCO_2e$ = US dollars per tonnes of carbon dioxide equivalent; US$/yr = US dollars per year; Yr = year; ZEF = zero-emission fuel.

[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. In previous reports, all acceleration factors under 10 were rounded to the 10th place (e.g., 7.4), which is 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.

[b] The category of progress was adjusted for indicators categorized as exponential change likely, using methods outlined in Schumer et al. (2022), and so in these instances, the category of progress identified does not always match the acceleration factor calculated using a linear trendline. See chapters for additional information.

[c] Indicators for forests and land experience high interannual variability in historical data due to both anthropogenic and natural causes. Accordingly, we use 10 years instead of 5 years to calculate the linear trendline where possible.

[d] 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) is used to estimate the historical rate of change, rather than a linear trendline.

[e] Energy intensity is the amount of energy used per square meter of floor area, including heating, cooling, and appliances. Publicly available data report only energy intensity trends for all buildings combined, not for residential and commercial buildings separately. In calculating acceleration factors, we use this combined energy intensity trend and assume that the historical rate of change is the same for both types of buildings.

[f] This target is not global in scope, rather it focuses on reducing energy intensity in key regions and countries. See Section 3 for more details.

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

[h] Indicators for forests and land experience high interannual variability in historical data due to both anthropogenic and natural causes. Accordingly, we use 10 years instead of 5 years to calculate the linear trendline where possible. But for this indicator, we calculated a 7-year trendline using data from 2015 to 2021 due to temporal inconsistencies in the data before and after 2015 (Weisse and Potapov 2021).

[i] High-consuming regions include the Americas, Europe, and Oceania.

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

[j] Due to limited data, the linear trendline for this indicator was calculated using four years of data, rather than five years.

[k] Carbon prices in the target are expressed in 2015 dollars.

[l] Data on capital expenditure by G20 state-owned entities on fossil fuels was not available for 2020, so the 2019 figure of $250 billion is used.

[m] Historical data from Murray et al. (2022), which estimated mangrove loss for six three-year epochs. Gross loss was divided by the number of years in each epoch to determine the average annual loss rate, and a linear trendline was calculated using these data.

[n] Murray et al. (2022) estimated that 0.18 Mha of gross mangrove gain occurred from 1999 to 2019, only 8 percent of which can be attributed to direct human activities, such as mangrove restoration. Accordingly, this report does not use gross mangrove gain to approximate mangrove restoration. We estimate the most recent historical data point for mangrove restoration by taking 8% of the total gross mangrove gain from 1999-2019. See Schumer et al. (2022) for more information.

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

Power

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

The global power system is in the midst of a major transformation. The deployment of renewables is accelerating, and their costs have declined sharply since 2010 (IRENA 2022b). In many regions, renewables are competing against—and often undercutting—fossil fuel generation, especially coal. The share of zero-carbon power generation (renewables and nuclear) has increased over the past decade, from 32.3 percent in 2010 to 36.4 percent in 2019. This has driven decreases in the carbon intensity of electricity generation, which is heading in the right direction (from 40.4 grams of carbon dioxide per kilowatt-hour in 2010 to 36.9 in 2019) but needs to be moving about five times faster. However, coal-based electricity generation continues to rise in some regions, especially in China, offsetting declining power sector emissions elsewhere. This is happening despite consistent decreases in the share of coal in electricity generation. Meanwhile, the share of electricity generation from fossil gas is ramping up after a decline earlier in the COVID-19 pandemic. As a result, emissions from the power system hit an all-time high in 2021. This

highlights a need not only to increase power generation from zero-carbon sources but also to retire fossil fuel–powered generation while decreasing energy demand.

Additionally, as a result of Russia's invasion of Ukraine, there is renewed interest in fossil fuels that could have long-lasting impacts on energy supply. Specifically, the slowdown of gas delivery from Russia to the European Union has driven a rethinking of energy policy in the bloc, at least temporarily. For example, the shortage of fossil gas has led countries like Austria, Germany, Italy, and the Netherlands to restart shuttered coal generation plants, although they claim these are short-term measures that do not interfere with long-term coal phaseout plans (Morris et al. 2022). Leaders of the G7 countries have endorsed new investments in natural fossil gas abroad as a "temporary" measure to address the supply crunch (G7 2022b).

There is an urgent need to divert the power sector away from fossil fuels toward zero-carbon technologies. The global response to move away from Russian oil and gas should be the impetus for a faster energy transition. The costs of clean energy technologies in mature markets are no longer the main barrier preventing the transition from taking off more quickly (although cost barriers in developing countries still need to be addressed). Rather, the principal obstacles are the actions, and the inaction, of governments, in so many ways the gate-keepers to how quickly zero-carbon technologies are deployed. Governments control the planning, land-use, and grid-connection rules; they control the quantity of zero-carbon power contracted in auctions and feed-in tariffs; they design the policies and regulations to address the uncosted negative externalities from fossil fuels; and they also make decisions about whether to pursue further expansions in fossil fuel power and avoid shutting down fossil infrastructure before the end of its economic life, which leaves less room for zero-carbon growth. Also, in the context of equitable transitions, governments of developed countries decide how much financial assistance they provide to accelerate the clean energy transition in developing countries. Ultimately, government actions will prove decisive in aligning the power system with 1.5°C pathways.

Buildings

- ✕ Energy intensity of building operations (% of 2015 levels)
- ? Carbon intensity of building operations (kgCO_2/m^2)
- ? Retrofitting rate of buildings (%/yr)

The necessary transition toward highly efficient and electrified buildings is advancing only slowly, despite widespread availability of required technologies and know-how. GHG emissions from buildings stem primarily from the energy used for space heating and cooling, water heating, lighting, cooking, and powering appliances. Although the energy intensity of building operations (energy use per unit of floor area) declined during the 2000s and early 2010s, progress has slowed in recent years, and remains well off track for meeting 1.5°C-aligned targets for 2030 in both residential and commercial buildings. Indeed, to get on track within the decade, the energy intensity of residential building operations must decrease seven times faster, while the energy intensity of commercial building operations must decrease five times faster.

Increased demand for electricity now outpaces some of the earlier improvements made in energy efficiency, partly driven by hotter summers and the consequent demand for more cooling than ever before (IEA 2020h). Similarly, the pace of improvement in the carbon intensity of buildings is insufficient to counteract increases in floor area, which has been growing at a rate of 2 percent per year, and absolute emissions of CO_2 from buildings continue to rise (IEA 2020h, 2019b, 2020b).

Most new buildings are still not being designed and constructed as zero-carbon buildings with high energy efficiency, electric heating and cooking equipment, or on-site renewable energy wherever feasible. This remains a top priority for decarbonizing the system. Simultaneously, existing buildings also need to be retro-fitted to meet the same zero-carbon standard. The IEA states that deep retrofitting rates are currently less than 1 percent per year (IEA 2020g, 2021i), so a significant ramp up in effort will be critical for reaching the rate of 2.5 to 3.5 percent per year needed by the end of the decade.

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 steel)

Since 2000, total GHG emissions from industry, which encompasses the production of goods and materi-als like cement, steel, and chemicals, as well as the construction of buildings, roads, bridges, and other infrastructure, have risen faster than in any other system (Minx et al. 2021). Reductions in industrial emissions intensity (i.e., emissions per unit of production) achieved to date have historically been driven primarily by the adoption of best available technologies that improve energy efficiency. However, rising demand for industrial products is now offsetting these efficiency gains and resulting in increased absolute levels of emissions. Marginal changes will not be sufficient to decarbonize the system.

A major push for increased efficiency, wide-scale electrification of industrial processes, and introduction of zero-carbon technologies for emissions-intensive industries, such as cement and steel, is critically needed, along with adoption of circular economy principles. However, progress across most of these endeavors to date has been slow.

For instance, globally, the carbon intensity of steel production—one of the two most emissions-intensive industrial processes—is headed in the wrong direction altogether, likely due to an increased share of blast furnace–based steel production in China, which produces more than half of global steel. Simultaneously, the carbon intensity of cement production—the other most emissions-intensive industrial subsector—is well off track from its 1.5°C-aligned 2030 targets, requiring progress to accelerate by more than 10 times the recent pace of change. Much faster deployment of low-carbon steel and cement plants and low-carbon cement alternatives will be required this decade and beyond to ensure that both of these high-emitting subsectors get on track.

Global green hydrogen production, which will be needed as a carbon-neutral fuel and feedstock for decarbonizing several industrial processes, as well as in other sectors such as power and transport, has begun to ramp up in recent years, demonstrating potential for exponential growth. However, comprising just 0.03 percent of all hydrogen production in 2020 (IEA 2021e), green hydrogen, produced through electrolysis using clean electricity and water, will need to be scaled up enormously to meet even the lowest estimates of future needs in the industrial system. The only indicator in the industry system that is heading in the right direction at a promising but insufficient speed is the share of electricity in the industry sector's final energy demand, which should hit 35 percent by 2030 to maintain 1.5°C-alignment, and needs to accelerate by a factor of 1.7 compared to recent progress. Increased efforts to accelerate this trend should be prioritized and increased in the longer term to meet the 2050 target, while simultaneously rapidly scaling up capacity for innovative steel, cement, and hydrogen solutions.

Transport

- ! Share of electric vehicles in light-duty vehicle sales (%)
- ! Share of battery electric vehicles and fuel cell electric vehicles in bus sales (%)
- × Number of kilometers of rapid transit (metro, light-rail, and bus rapid transit) per 1 million inhabitants (in the top 50 emitting cities) (km/1M inhabitants)
- × Number of kilometers of high-quality bike lanes per 1,000 inhabitants (in the top 50 emitting cities) (km/1,000 inhabitants)
- × Share of electric vehicles in the light-duty vehicle fleet (%)
- × Share of battery electric vehicles and fuel cell electric vehicles in medium- and heavy-duty vehicle sales (%)
- × Share of sustainable aviation fuels in global aviation fuel supply (%)
- × Share of zero-emission fuels in maritime shipping fuel supply (%)
- ↓ Share of kilometers traveled by passenger cars (%)
- ? Carbon intensity of land-based passenger transport (gCO_2/pkm)

Over the past three decades, economic development and increasing car dependency has caused steady increases in GHG emissions from transport, and efforts to reverse this trend are only slowly progressing. Transforming the transportation system will require a series of critical shifts. First, the build-out of shared, public, and nonmotorized transport, such as rapid transit and bicycling in cities, is headed in the right direction but needs to accelerate significantly to meet climate goals. Cities are slowly building out more rapid transit and high-quality bike lanes to make low-carbon modes of travel more accessible. Second, private car use must decline. Yet the share of kilometers traveled by passenger cars increased from 39 percent in 2015 to 44 percent in 2020 (ITF 2021).

Third, and where we have seen the most progress so far, is the rise of zero-carbon cars and trucks. The share of electric vehicles (EVs) in light-duty vehicle sales has begun to take off, reaching almost 9 percent in 2021, a doubling from the year before (BNEF 2022a). And with supportive policies and investments, EVs are becoming more cost-competitive with internal combustion engine vehicles in many major markets. Global sales of zero-carbon medium- and heavy-duty vehicles (MHDVs) remain low, reaching roughly 0.2 percent of total sales in 2021 (BNEF 2022a), but this represents a doubling from 2020. The global share of zero-carbon bus sales has increased by a factor of 22 in less than a decade, driven largely by impressive sales in China.

Finally, the maritime shipping and aviation systems must transition to zero-carbon technologies. While the share of sustainable aviation fuels in the global aviation fuel supply was less than 0.1 percent in 2020, there are signs that supply and use are beginning to grow, given the 21 million tonnes (metric tons) of purchase agreements between fuel suppliers and airlines or logistics companies (Mission Possible Partnership 2022a). Zero-emission fuels in maritime shipping have not yet reached commercialization, but a plethora of pilot and demonstration projects developing green hydrogen, ammonia, and synthetic fuels such as e-methanol could provide an avenue for producing liquid fuels with zero or net zero well-to-wake emissions (Global Maritime Forum 2022).

Forests and land

- ! Reforestation (total Mha)
- ✕ Deforestation (Mha/yr)
- ⇩ Mangrove loss (ha/yr)
- ? Mangrove restoration (total Mha)
- ? Peatland degradation (Mha/yr)
- ? Peatland restoration (total Mha)

Limiting global temperature rise to 1.5°C will require immediate action to protect, restore, and sustainably manage the world's natural carbon sinks and stores—particularly forests, peatlands, and mangroves. Together, these land-based measures could help mitigate between 4.2 gigatonnes of carbon dioxide equivalent ($GtCO_2e$) and 7.3 $GtCO_2e$ per year at relatively low costs (up to \$100/tCO_2e) from 2020 to 2050 (IPCC 2022b). Yet recent progress made in deploying these approaches remains largely insufficient, with net anthropogenic CO_2 emissions from land use, land-use change, and forestry reaching nearly 6.6 $GtCO_2e$ in 2019—or roughly 11 percent of GHG emissions globally (IPCC 2022b).

Effectively halting deforestation, peatland degradation, and mangrove loss delivers the lion's share of the cost-effective mitigation potential that land-based measures across high-carbon ecosystems can contribute to holding global warming to 1.5°C (Roe et al. 2021). Protecting these ecosystems, which collectively hold roughly 1,020 gigatonnes of carbon, will also prove critical to near-term climate action, as they can lose carbon rapidly after certain disturbances (Goldstein et al. 2020; Cook-Patton et al. 2021). Once released, much of this carbon is irrecoverable on policy-relevant timescales, effectively creating a permanent deficit in the world's remaining carbon budget for a 1.5°C future. It would take forests 6 to 10 decades to rebuild these lost carbon stocks, well over a century for mangroves, and many centuries to millennia for peatlands (Goldstein et al. 2020; Temmink et al. 2022).

But global efforts to protect these ecosystems remain well off track and heading in the wrong direction globally. Although permanent forest losses fell by 2 percent from 2020 to 2021, these rates are not declining fast enough to hold global warming to 1.5°C. From 2015 to 2021, deforestation occurred across an area roughly the size of Iraq (45 million hectares [Mha]), emitting a total of 25 $GtCO_2e$ (Hansen et al. 2013; Curtis et al. 2018; Turubanova et al. 2018; Tyukavina et al. 2022). Worse still, nearly half of these permanent losses (22 Mha) occurred within humid tropical primary forests, among the world's most important landscapes for carbon storage and biodiversity (Harris et al. 2021; Mackey et al. 2020; Gibson et al. 2011). Peatlands and mangroves have also suffered losses in recent years. Although they slowed dramatically from roughly 1–2 percent per year in the late 20th century (Friess et al. 2019) to just 0.13 percent per year from 2000 to 2016 (Goldberg et al. 2020), annual rates of gross global mangrove loss are once again ticking upward. Similarly, from 1990 to 2019, draining peatlands for agriculture accelerated across Southeast Asia (Conchedda and Tubiello 2020), a region that contains much of the world's tropical peatlands.

Although protecting forests, peatlands, and mangroves should be prioritized (Cook-Patton et al. 2021), achieving the Paris Agreement's 1.5°C temperature limit also will require large-scale restoration (IPCC 2022b). But here, too, global progress toward near-term targets remains off track for reforestation; although data are limited for peatlands and mangroves, available evidence indicates that recent efforts in restoring both ecosystems are also inadequate. To reforest 100 Mha by 2030, for example, the world would need to reforest an area roughly the size of South Korea (10 Mha) each year over this decade.

Large-scale commodity production remains the primary driver of deforestation and degradation across these high-carbon ecosystems, with a significant share of the demand for these commodities originating in the world's wealthiest countries. By one estimate, roughly 40 percent of GHG emissions from deforestation were embodied in internationally traded commodities from 2010 to 2014 (Pendrill et al. 2019b), with developed countries and emerging economies importing an increasingly large share of deforestation embodied in commodities (Pendrill et al. 2019a).

Changing course to meet global demand for these commodities, while effectively halting ecosystem losses, enabling large-scale restoration, and addressing other direct and indirect drivers of degradation will require actions from governments, financial institutions, companies, and civil society, spanning a diverse set of geographies. In countries containing these high-carbon ecosystems, strengthening national conservation policies (e.g., placing moratoria on conversion), securing land tenure, particularly for Indigenous Peoples and local communities, and improving policy coherence across sectors and at all levels of decision-making can help deliver land-based mitigation across these ecosystems. Some nations, particularly least developed countries, may need additional technical and financial assistance to overcome capacity constraints that often limit enforcement, while others may require broader governance reforms to reduce corruption. Financial institutions, companies, and consumer country governments also have a critical role to play in achieving 1.5°C-aligned targets for forests, peatlands, and mangroves. All, for example, can help raise the over $400 billion per year in public and private finance needed by 2050 (IPCC 2022b), as well as align broader financial flows with 1.5°C pathways by, for example, halting investments in companies that have yet to take steps to eliminate deforestation and related human rights abuses from their supply chains.

Food and agriculture

- ! Ruminant meat productivity (kg/ha/yr)
- ✕ Crop yields (t/ha/yr)
- ✕ Ruminant meat consumption (kcal/capita/day)
- ⇩ Agricultural production GHG emissions ($GtCO_2e$/yr)
- ? Share of food production lost (%)
- ? Food waste (kg/capita/yr)

The global food system needs to transform from its current state to one that can feed nearly 10 billion people while lowering GHG emissions—without expanding agriculture's land area or negatively impacting biodiversity. Achieving these goals in the coming decades cannot be done without significant changes to food production and consumption (Clark et al. 2020). Critical shifts include halting agricultural expansion, sustainably increasing crop yields and ruminant meat productivity, changing on-farm practices and technologies, dramatically lowering food loss and waste, and reducing ruminant meat consumption in high-income countries.

Direct emissions from crop and livestock production increased 2 percent between 2015 and 2019. While it is encouraging that agricultural emissions are not growing quickly, targets for 2030 and 2050 call for significant reductions, so a major step change is needed. Recent growth in crop yields will need to accelerate by six times in the next decade. Per capita consumption of beef, lamb, and goat meat across high-consuming regions would simultaneously need to decline five times faster to realize 2030 targets. Remaining ruminant meat needs to be produced as efficiently as possible. Ruminant meat productivity per hectare increased to a new high in 2019 as a result of improvements in feed efficiency, pasture productivity, and grazing systems, and increases in meat production per animal (Searchinger et al. 2019b). While progress on these productivity gains is heading in the right direction, improvements are too slow to meet 2050 targets. Regarding food loss and waste, the most recent global estimates remain that 14 percent of global food production is still lost between the farm gate and processing stages of the food supply chain (FAO 2019), and another 17 percent of food at the retail level is wasted in households, food service, and retail (UNEP 2021d).

Technological carbon removal

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

The most recent science indicates that large-scale carbon dioxide removal (hereafter referred to as carbon removal) is needed to meet the Paris Agreement's 1.5°C temperature limit. This includes approaches that are generally considered natural, or land-based, as well as more technological approaches. How much carbon removal is ultimately needed is uncertain, with estimates varying widely from less than 1 $GtCO_2$ per year to more than 14 $GtCO_2$ in 2050 (IPCC 2022b). And it depends directly on the level of near-term emissions reduction; more rapid emissions reductions are a top priority in the near term and can help reduce our future reliance on carbon removal technologies. Carbon removal is needed to address residual emissions for which abatement options do not become available or are too expensive, and in the longer term is also needed to reduce atmospheric carbon dioxide concentrations closer to pre-industrial levels. Developing a broad portfolio of approaches will reduce the risks and balance the trade-offs associated with each—for example, technological carbon removal is generally more costly but also more permanent.

Today less than 1 million tonnes of carbon dioxide ($MtCO_2$) per year are removed through what are generally considered to be technological approaches, or less than 1 percent of this report's 2030 target of 75 $MtCO_2$ per year. However, public and private investment is growing, and the first set of large-scale projects is planned to come online in the next several years. Faster progress will require reducing cost, expanding enabling infrastructure (e.g., well-characterized, accessible geologic storage), expanding clean energy capacity, increasing demand for carbon removal, improving governance frameworks and prioritizing equity and sustainability among other issues, and building public support for large-scale carbon removal (NASEM 2019; Amador et al.

2021). In the longer term, it will be crucial to determine who will pay for large-scale carbon removal—across the public and private sectors (ETC 2022; McCormick 2022).

Finance

✕	Global total climate finance (trillion $/yr)
✕	Global public climate finance (trillion $/yr)
✕	Global private climate finance (trillion $/yr)
✕	Share of global emissions under mandatory corporate climate risk disclosure (%)
✕	Median carbon price in jurisdictions with emissions with pricing systems (2015$/t$CO_2$e)
✕	Total public financing for fossil fuels (billion $/yr)

Transforming power, buildings, industry, transport, forests and land, and food and agriculture, as well as scaling up technological carbon removal, all require significant increases in finance flows, as well as a broader transformation of the financial system to be aligned with climate goals (IPCC 2022b). Yet the global financial system is a major underwriter of GHG emissions and carbon lock-in, with many of the world's leading financial institutions investing in fossil fuels, commodities that drive deforestation, and other activities that would put the Paris Agreement's 1.5°C limit out of reach. Developing countries are being hit particularly hard by the ongoing impacts of climate change and the pandemic, rising food and energy prices, increasing interest rates, and currency depreciation (United Nations 2022a, 2022b, 2022c), and will require support from richer nations to enable a just transition to a net-zero and climate-resilient world.

Climate finance is growing overall but nowhere near at the pace needed—more than 10 times historical growth rates—to meet investment needs (Buchner et al. 2021). Global public climate finance (comprising domestic and international flows) fell in 2020, as governments shifted focus to urgent healthcare needs and social spending to deal with COVID-19. Governments largely missed the opportunity to ensure that the massive public spending in response to the pandemic was oriented toward a green recovery (UNEP 2021c). Meanwhile, global tracked private climate finance has grown more slowly than public climate finance over the past five years. The Glasgow Financial Alliance for Net Zero commitment by many institutions to align their $130 trillion in assets to be net zero by 2050 (GFANZ 2021) is notable for its size and potential, but its ambition is not yet manifesting in near-term capital shifts that will be necessary to achieve a net-zero world. The total amount of global climate finance needs to increase more than eightfold to reach a Paris-aligned target of $5.2 trillion per year by 2030.

Although some governments and corporate actors are setting positive examples as they take concrete policy steps to increase finance, much more work is needed. There is a growing movement from governments to adopt mandatory climate-related disclosures in their regulatory and supervisory frameworks for corporate actors, and the private sector is also building positive momentum with improvements in voluntary disclosures and announcements of net-zero targets. The adoption of carbon pricing is also growing, with more jurisdictions around the world implementing pricing mechanisms. Yet current carbon prices are insufficient and far from being aligned with what is necessary to limit warming to 1.5°C. Indeed, there was little progress in expanding carbon pricing coverage in 2022 (World Bank 2022b).

While the pandemic and subsequent oil price crash caused fossil fuel subsidies to drop significantly in 2020, there are signs this has rebounded (IEA 2022e). Demand for fossil fuels has increased as countries have emerged from pandemic shutdowns, and the Russian invasion of Ukraine has led some countries to pursue alternative sources of supply, leading to increasing subsidies as governments seek to boost production and protect consumers from price increases. Comprehensive global data on fossil fuel subsidies are not yet available for 2021 or 2022, but production and consumption subsidies in 51 major economies covering 85 percent of the world's energy supply nearly doubled from 2020 levels to $697 billion in 2021, 17 percent above 2019 levels (OECD 2022b). If international public funding for fossil fuels is shifted into clean energy, as 34 countries at COP26 and the G7 have pledged to do, it could help deliver on climate finance commitments, including the $100 billion goal (OCI 2022; COP26 Presidency 2021; G7 2022a).

TABLE ES-1 | Summary of global progress by system

RECENT TRENDS IN SECTORAL GHG EMISSIONS	STATUS OF INDICATORS	COMMONLY CITED BARRIERS TO CHANGE	COMMONLY CITED ENABLING CONDITIONS
Power			
10% increase in emissions from 2010, reaching 13.7 $GtCO_2e$ in 2019 3.1% drop in 2020, due primarily to COVID-19; however, preliminary data for 2021 indicate a rebound	✕ Carbon intensity of electricity generation (gCO_2/kWh) ! Share of zero-carbon sources in electricity generation (%) ✕ Share of unabated coal in electricity generation (%) ⇩ Share of unabated fossil gas in electricity generation (%)	• Powerful vested interests in fossil fuels • Perceived investment risks in clean energy projects • Unsupportive policies and incentives; e.g., subsidies of fossil fuels • Electricity markets not calibrated for intermittent and decentralized renewable systems • Transmission and distribution systems not yet suited for intermittent and decentralized renewable systems • Early closure of carbon intensive infrastructure incurs financial losses for owners • Storage scaling constraints related to energy density, capacity, and cost • Reforming supply can lead to disruption in employment at power stations and along the supply chain	• Increased support for climate-focused political parties and organizations seeking to highlight the fossil fuel industry's influence on power • Government and private investments in transmission and distribution network upgrades and expansion • Coal phaseout and renewable energy targets • Government and private sector R&D programs • Early adoption of grid-scale batteries • Energy efficiency programs to manage final energy demands • National demand-response programs, which reduce peak demands, smooth the variability in renewable energy, and save consumers money • Implementation of retraining programs, economic diversification, and relocation support
Buildings			
7% increase in emissions from 2010, reaching 9.8 $GtCO_2e$ in 2019 Decline of 10% in direct and indirect emissions from buildings in 2020 relative to 2019; however, preliminary data for 2021 indicate full rebound	✕ Energy intensity of building operations (% of 2015 levels) ? Carbon intensity of building operations ($kgCO_2/m^2$) ? Retrofitting rate of buildings (%/yr)	• Competing priorities for all actors with a lack of incentive to prioritize energy efficiency • Up-front costs and long payback periods of zero-carbon buildings • Split incentives whereby property owners are responsible for upgrades but do not reap benefits of lower energy bills • Limited knowledge and awareness of the appropriate technologies • Lack of appropriate training among architects, engineers, and contractors	• Development of government and corporate decarbonization and roadmaps for energy efficiency in buildings to set out direction of change • Stringent building energy and decarbonization codes for new buildings that are enforced • Efficiency standards and regulations for equipment and appliances • Requirements for property owners to make energy efficiency upgrades and change energy contract setups to lower perceived investment risks • Direct financial support from governments for zero-carbon new builds and retrofits, including grants and tax rebates • Stakeholder engagement and shifting incentives to overcome multiactor challenges

TABLE ES-1 | Summary of global progress by system (continued)

RECENT TRENDS IN SECTORAL GHG EMISSIONS	STATUS OF INDICATORS	COMMONLY CITED BARRIERS TO CHANGE	COMMONLY CITED ENABLING CONDITIONS
Industry			
12% increase in emissions from 2010, reaching 17.5 $GtCO_2e$ in 2019 10% reduction in emissions in 2020; however, preliminary data for 2021 indicate a rebound	! Share of electricity in the industry sector's final energy demand (%) ✕ Carbon intensity of global cement production ($kgCO_2$/t cement) ⇩ Carbon intensity of global steel production ($kgCO_2$/t steel) ✕ Green hydrogen production (Mt)	• Large investment needs in R&D, piloting, and demonstration • Distorted energy prices and not economically competitive renewable-based fuels • Lack of capacity (e.g., institutional, technical, and human capacity) • Limited access to capital • Capital cost of equipment • Long economic lifetimes of industrial plants	• Supportive policies to enhance production of low-carbon industrial products, including procurement, carbon pricing, and standards • Regulations, information and training, energy audits and digital management systems, and financial incentives for improving energy efficiency • Investments in research and development to produce and significantly reduce costs of new technologies and innovations • Technology transfer and investments in developing economies • Establishment of national green hydrogen targets for production and consumption
Transport			
17% increase in emissions from 2010, reaching 8.9 $GtCO_2e$ in 2019 10% drop in 2020 due to COVID-19; however, preliminary data for 2021 indicate a rebound in emissions from road transport and, to a lesser extent, those from aviation	⇩ Share of kilometers traveled by passenger cars (%) ✕ Number of kilometers of rapid transit (metro, light-rail, and bus rapid transit) per 1 million inhabitants (in the top 50 emitting cities) (km/1M inhabitants) ✕ Number of kilometers of high-quality bike lanes per 1,000 inhabitants (in the top 50 emitting cities) (km/1,000 inhabitants) ? Carbon intensity of land-based passenger transport (gCO_2/pkm) ! Share of electric vehicles in light-duty vehicle sales (%) ✕ Share of electric vehicles in the light-duty vehicle fleet (%) ! Share of battery electric vehicles and fuel cell electric vehicles in bus sales (%) ✕ Share of battery electric vehicles and fuel cell electric vehicles in medium- and heavy-duty vehicle sales (%) ✕ Share of sustainable aviation fuels in global aviation fuel supply (%) ✕ Share of zero-emission fuels in maritime shipping fuel supply (%)	• Dedication of most public and private funds spent on transportation infrastructure globally to supporting roads and highways • Land use decisions leading to outward urban expansion • Subsidies for the use of private vehicles that fail to fully account for costs • High up-front cost of zero-emission passenger vehicles, buses, and medium- and heavy-duty vehicles • Fossil fuel subsidies • Insufficient charging infrastructure for EVs • Lack of investments and policies needed to develop, commercialize, and scale zero-emission fuels	• Increased public spending on both infrastructure and operations of alternative transport modes • Changes to zoning regulations • Policies such as congestion pricing that reflect the costs of automobility • Demand-side measures to increase EV adoption in the short term, including consumer subsidies and regulations • Zero-emission zones where ICE vehicles are restricted or not allowed • Sales mandates for manufacturers • More rapid deployment of charging infrastructure, including by redesigning utility rates to make public charger maintenance more attractive and offering land to charger networks at reduced prices • R&D for zero-emission aviation and shipping fuels • Policy support to promote zero-emission aviation and shipping fuels

TABLE ES-1 | Summary of global progress by system (continued)

RECENT TRENDS IN SECTORAL GHG EMISSIONS	STATUS OF INDICATORS	COMMONLY CITED BARRIERS TO CHANGE	COMMONLY CITED ENABLING CONDITIONS
Forests and land			
Increase in GHG emissions from AFOLU, reaching 13 $GtCO_2e$ in 2019 and growing 1.6% from 2010 to 2019; but trends in the direction of net anthropogenic CO_2 emissions for land use, land-use change, and forestry, specifically, remain unclear	× Deforestation (Mha/yr) ! Reforestation (total Mha) ? Peatland degradation (Mha/yr) ? Peatland restoration (total Mha) ⇩ Mangrove loss (ha/yr) ? Mangrove restoration (total Mha)	• Weak policies that do not adequately protect high-carbon ecosystems from conversion or promote restoration • Conflicting policies that undercut efforts to protect and restore high-carbon ecosystems by encouraging development across them • Limited implementation and enforcement of existing conservation policies due to complex, fragmented governance, resource constraints, and corruption, among other factors • Insecure, unclear land tenure • Misaligned finance, as well as insufficient public and private finance dedicated to the protection and restoration of ecosystems • Growing demand for commodities that drive ecosystem loss and degradation	• Stronger national conservation policies, including placing moratoria on the conversion of high-carbon ecosystems, establishing and expanding protected areas, financially incentivizing conservation (e.g., through payment for ecosystem services), encouraging community forest management, and legally recognizing and upholding Indigenous Peoples' land rights • Improved policy coherence across consumer and producer countries to enable more effective implementation across sectors and at all levels of decision-making • Governance reforms, as well as technical and financial assistance, to support enhanced enforcement • Increased public and private finance for land-based mitigation measures • Improved monitoring, particularly for peatlands and mangroves, to track and inform implementation of commitments to halt and reverse ecosystem loss • More ambitious commitments and action from financial institutions and companies responsible for deforestation paired with supportive, complementary policies from producer and consumer country governments
Food and agriculture			
Increase in GHG emissions from AFOLU, reaching 13 $GtCO_2e$ in 2019 and growing 1.6% from 2010 to 2019; however, COVID-19's impacts on agricultural production emissions, specifically, remain unclear	⇩ Agricultural production GHG emissions ($GtCO_2e$/yr) × Crop yields (t/ha/yr) ! Ruminant meat productivity (kg/ha/yr) ? Share of food production lost (%) ? Food waste (kg/capita/yr) × Ruminant meat consumption (kcal/capita/day)	• Behavior change (e.g., diets) is difficult • Perverse agricultural subsidies • Lack of finance for smallholder farmers • RD&D needed for promising lower-emissions technologies • Practices and technologies that reduce agricultural production emissions may entail additional costs to producers • Lack of land tenure	• Incentives and regulatory frameworks to help farmers shift to more climate-friendly practices and technologies once they are available • RD&D for new technologies (e.g., feed additives, nitrification inhibitors for fertilizers, lower-methane rice varieties, alternative proteins) • Governments and businesses promoting low-carbon diet shifts • Technical assistance for farmers to adapt to climate change and improve yields • Supportive finance, including redirecting perverse agricultural subsidies • Produce and protect policies that encourage sustainable intensification and ecosystem protection

TABLE ES-1 | Summary of global progress by system (continued)

RECENT TRENDS IN SECTORAL GHG EMISSIONS	STATUS OF INDICATORS	COMMONLY CITED BARRIERS TO CHANGE	COMMONLY CITED ENABLING CONDITIONS
Technological carbon removal			
N/A	✕ Technological carbon removal ($MtCO_2$/yr)	• Carbon removal is largely a public good, so needs to be supported by subsidies or other types of support • High costs and insufficient number of entities willing to pay • Insufficient enabling infrastructure (e.g., CO_2 transport infrastructure) • Lack of broad public support for large-scale carbon removal • Lack of comprehensive governance frameworks • BECCS, and other biomass-based carbon removal technologies, present concerns related to sourcing biomass feedstocks and potential food security, biodiversity, and emissions impacts of indirect land-use change	• Government investment in research, development, and demonstration • Government support for carbon removal projects • Build-out of enabling infrastructure, such as geologic sequestration facilities, CO_2 transport infrastructure, and abundant renewable and zero-carbon energy • Robust governance structures that help avoid overreliance on carbon removal at the expense of emissions reduction, improve monitoring and verification capacity while ensuring credibility and consistency, and ensure consideration of economic, environmental, and other trade-offs on a project-by-project basis • Corporate investment and corporate commitments that do not overrely on carbon removal
Finance			
N/A	✕ Global total climate finance (trillion US$/yr) ✕ Global public climate finance (trillion $/yr) ✕ Global private climate finance (trillion $/yr) ✕ Share of global emissions under mandatory corporate climate risk disclosure (%) ✕ Median carbon price in jurisdictions with pricing systems (2015/tCO_2e) ✕ Total public financing for fossil fuels (billion/yr)	• Capital continues to be misallocated toward high-emissions activities • Vested interests oppose reforms to direct investments away from fossil fuels and toward clean energy • Lack of public support for new taxes or an end to fossil fuel subsidies • Perceived free-rider problem • Countries with high debt levels and/or poor credit ratings may struggle to raise additional resources • Institutional rules can prohibit some governments from investing in climate solutions and regulating finance	• Greater leadership from the world's wealthiest countries, financial institutions, and companies to support financial reforms, translate commitments into action, and boost climate finance, including richer countries increasing international funding to developing countries • Shifts in social norms to build public support for policies and mechanisms to transform financial systems • Reforms in government institutions to be more transparent, responsive, and representative to help reduce the influence of special interests in the policymaking process • Removal of institutional barriers to climate investments and the creation of greater fiscal space through debt relief • Increased government spending, including through more tax revenues, debt issuance, or shifting spending from climate-misaligned areas. • Establishment of carbon pricing mechanisms that rise over time, address leakage through cooperation or border adjustment mechanisms, and are paired with policies that address equity impacts • Adoption of incentives and regulations, including financial policies and regulations that shift private investment flows.

Notes: %/yr = percent per year; 2015 US$/$tCO_2e$ = 2015 US dollars per tonnes of carbon dioxide equivalent; AFOLU = agriculture, forestry, and other land uses; BECCS = bioenergy with carbon capture and storage; CO_2 = carbon dioxide; EV = electric vehicles; gCO_2/kWh = grams of carbon dioxide per kilowatt-hour; gCO_2/pkm = grams of carbon dioxide per passenger kilometer; GHG = greenhouse gas; $GtCO_2e$ = gigatonnes of carbon dioxide equivalent; $GtCO_2e$/yr = gigatonnes of carbon dioxide equivalent per year; ha/yr = hectares per year; ICE = internal combustion engine; kcal/capita/day = kilocalories per capita per day; kg/capita/yr = kilograms per capita per year; kg/ha/yr = kilograms per hectare per year; $kgCO_2/m^2$ = kilograms of carbon dioxide per square meter; $kgCO_2$/t = kilograms of carbon dioxide per tonne; km/1,000 inhabitants = kilometers per 1,000 inhabitants; km/1M inhabitants = kilometers per 1 million inhabitants; Mha/yr = million hectares per year; Mt = million tonnes; $MtCO_2$/yr = million tonnes of carbon dioxide per year; R&D = research and development; RD&D = research, development, and demonstration; t/ha/yr = tonnes per hectare per year; total Mha = total million hectares; US$/yr = US dollars per year.

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

SECTION 1

Methodology for Assessing Progress

This section provides a brief summary of this report's methodology. A more detailed explanation can be found in the accompanying technical note (Schumer et al. 2022). Please see this publication for more information on our selection of systems, targets, indicators, datasets, and enabling conditions, as well as our methods for assessing progress toward near-term targets.

Transformations, critical shifts, targets, and indicators

In modeled pathways that limit global temperature rise to 1.5°C above preindustrial levels with no or limited overshoot, greenhouse gas (GHG) emissions peak immediately or before 2025 at the latest, and then fall by a median of 43 percent from 2019 levels by 2030 (IPCC 2022b). 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 nearly all major systems—power, buildings, industry, transport, forests and land, and food and agriculture[1]—as well as the immediate scale-up of climate finance and carbon removal technologies to compensate for the significant proportion of the carbon budget that we have already spent and residual GHG emissions that will likely prove difficult to eliminate altogether (IPCC 2022b).

This report translates these transformations into a set of critical shifts for each system, as well as identifies key changes that must occur to support the rapid scale-up of carbon removal technologies and climate finance. Almost all must happen simultaneously to overcome the deep-seated carbon lock-in common to these systems (Seto et al. 2016). These shifts, however, are not comprehensive; rather, they form a priority set of actions needed to achieve the Paris Agreement's 1.5°C temperature goal.[2]

As an example, the global food system needs to transform from its current state to one that can feed nearly 10 billion people without expanding agriculture's land footprint or negatively impacting biodiversity, while also lowering GHG emissions. To achieve this systemwide transformation, multiple shifts must occur, including significant gains in cropland and livestock productivity, dramatic reductions in food loss and waste, limits on the overconsumption of ruminant meat, and rapid declines in GHG emissions from a wide range of agricultural production processes, such as rice cultivation, enteric fermentation, and chemical fertilizer application.

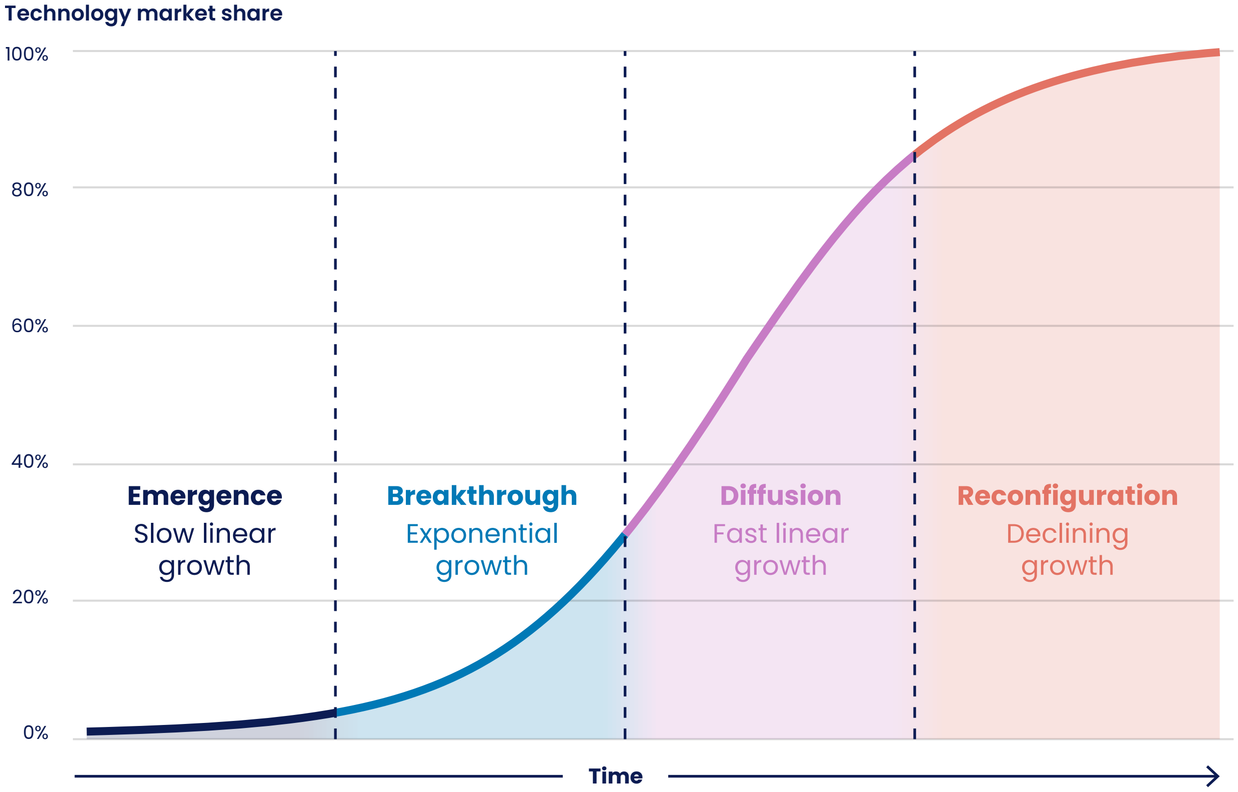
For each shift featured in this report, we identify global near-term and long-term targets—typically for 2030 and 2050, respectively—that are aligned with pathways limiting global temperature rise to 1.5°C. Although we do not systematically consider equity or biodiversity impacts in our target selection[3], we do apply additional criteria where possible, such as environmental and social safeguards and cost-effectiveness. For each target, we then select corresponding indicators with historical data to assess global progress made toward the target. 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.

Assessment of global progress

In this report, we provide a snapshot of global progress made toward holding warming to 1.5°C by assessing whether each indicator is on track to reach its near-term targets. To do so, we collect historical data for each indicator, relying on datasets that are open, independent of bias, reliable, and consistent. We aim to use the most recent data, but there is often a time lag before data become available (between 1 and 3 years for most indicators, but a handful lag by over 10 years), and, as such, the year of most recent data varies among indicators. In some cases, data limitations prevent us from evaluating how the current level of effort measures up against 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 way would be to assume that growth continues at its current rate of change following a linear trajectory, and, indeed, we use this method for many of our indicators. However, it is unlikely that all indicators will follow a linear path. The adoption of new technologies, specifically, has often followed a rough S-curve trajectory. At the emergence stage of an S-curve, progress is linear and slow. Then, once a breakthrough is achieved, it accelerates exponentially. This exponential growth continues until the technology reaches its maximum speed of uptake. This is the steepest part of the curve, which is linear again but growing at a much faster rate. Most of the diffusion—when the technology becomes integrated as the status quo—occurs during this stage. Finally, as the technology approaches a saturation point, the growth gradually slows down once again. The exact shape of such a curve is highly uncertain, and technologies can encounter obstacles that may alter or limit their growth, but it is clear that a purely linear assessment is insufficient in these cases. Given the right conditions (e.g., supportive policies), adoption of new technologies can reach positive tipping

FIGURE 1 | Illustration of an S-curve



Source: Authors; adapted from Boehm et al. (2021) and Grubb et al. (2021b).

points, when self-amplifying feedbacks kick in to spur rapid, far-reaching change that can cascade from one system to another or from one geography to another (Box 1). Therefore, we consider S-curve dynamics in our assessment of progress (Figure 1).

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.

To assess global progress made toward 1.5°C-compatible targets for all indicators, including those that may follow roughly an S-curve trajectory, we follow the following steps for each indicator:

STEP 1: Determine each indicator's potential for nonlinear change

First, we evaluate the likelihood that each indicator will experience exponential change[4] and place indicators into one of three categories based on our understanding of the literature and consultations with experts:

Exponential change unlikely:
We identify indicators that we do not expect to follow the S-curve dynamics seen in technology diffusion, given that they do not specifically track technology adoption. These fall primarily within the forests and land, food and agriculture, and finance sections (e.g., reforestation, restoration, reducing food waste, increasing finance flows).

Exponential change likely:
We consider indicators 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 following S-curve dynamics, though it is not guaranteed that they will do so. These technologies are

BOX 1 | Tipping points and self-amplifying feedbacks

A tipping point—defined broadly as a critical threshold beyond which a system reorganizes often abruptly or irreversibly (IPCC 2022b)—can also be conceptualized as the inflection point on an S-curve. Reaching this threshold often allows a new technology to achieve a breakthrough and accelerate on its S-curve path. 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 different future states (Lenton et al. 2008; Lenton 2020).

Once tipping points are crossed, self-amplifying feedbacks 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 enables companies to distribute the high costs of improvements across a wider customer base. 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 share, 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). These reinforcing feedbacks spur adoption and help new innovations to supplant existing technologies (Victor et al. 2019).

Widespread adoption of new technologies, in turn, can 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, availability of jobs, 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. Thus, for technologies with adoption rates that are already growing nonlinearly or could be expected to grow at an exponential pace in the future, it is unrealistic to assess progress by assuming that future uptake will follow a linear trajectory (Abramczyk et al. 2017; Mersmann et al. 2014; Trancik 2014).

innovative, often displacing incumbent technologies (e.g., renewable energy, electric vehicles, and green hydrogen).

Exponential change possible:
Finally, we identify indicators that do not fall neatly within the first two categories, with most tracking technology adoption indirectly (e.g., those focused on carbon intensity). While many factors, such as increases in resource efficiency, may impact future changes in these indicators, adoption of zero- or low-emissions technologies will likely also have an impact on their future trajectories. Thus, although these indicators have generally experienced linear growth in the past, they could experience some unknown form of nonlinear, exponential change in the coming decades if the nonlinear aspects grow to outweigh the linear aspects. 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-emission power, which is expected to be nonlinear. If the nonlinear growth in zero-emission power overtakes the linear growth in efficiency, the trajectory of carbon intensity could follow an inverted S-curve.

STEP 2:
Assess progress based on acceleration factor

Next we calculate a linear trendline, also known as a line of best fit, from the most recent five years of historical data. For several indicators, most notably those in the forests and land system, we calculate a linear trendline based on the most recent 10 years of historical data to account for natural interannual variability.[5] We then extend this trendline out to 2030 and compare this projected value to the indicator's target for that same year.[6] Doing so enables us to assess whether recent progress made toward the target is on track or not (see underlying data in Appendix A).

We then calculate an "acceleration factor" for each indicator with sufficient historical data by dividing the average annual rate of change needed to achieve the indicator's near-term target[7] by the average annual rate of change derived from the historical five-year trendline. These acceleration factors quantify the gap in global action between current efforts and those required to hold global warming to 1.5°C. They indicate whether recent historical rates of change need to increase 2-fold, 10-fold, or 20-fold, for example, to meet near-term targets (Appendix B).[8]

We then use these acceleration factors to assign our indicators one of five categories of progress:

✓ **On track.** The recent 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.

! **Off track**. The historical rate of change is heading in the right direction at a promising yet insufficient pace. Indicators with acceleration factors between 1 and 2 fall into this category.

✕ **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. Indicators with acceleration factors of greater than or equal to 2 fall into this category.[9]

⇩ **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, as 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.

STEP 3:
Make additional adjustments for "exponential change likely" indicators

For indicators that are "**exponential change unlikely**," we use the linear trendline and associated acceleration factors to assign categories of progress. For indicators that are categorized as "**exponential change possible**," we also use the linear trendline and associated acceleration factors to assign categories of progress, but it is critical to note that these linear trendlines form a baseline or floor for action needed to achieve 1.5°C-aligned targets. If nonlinear change begins, progress may unfold at significantly faster rates than expected and the gap between the existing rate of change and required action will shrink.

However, for indicators categorized as "**exponential change likely**," adoption of new technologies will likely spur rapid, nonlinear change in the coming decades, and future trajectories of growth may resemble an S-curve (although this nonlinear change is by no means guaranteed). For these indicators, acceleration factors based on linear trendlines likely underestimate the pace of future change, as well as overestimate the gap in required action to reach the global targets. Therefore, we use the acceleration factor method only as a starting point for our evaluation of "**exponential change likely**" indicators, and then, if needed, we adjust the categorization to account for exponential change based on our qualitative research of the literature and expert consultations. This process is described in further detail in the accompanying technical note (Schumer et al. 2022).

Ultimately, determining whether "**exponential change likely**" indicators are on track or not carries considerable uncertainties. Accurately projecting adoption rates for new technologies that are just beginning to emerge or diffuse across society is an enormously difficult endeavor. Any small fluctuations in the initial growth rate will create statistical noise, which introduces uncertainty into predictions that can reach orders of magnitude (Kucharavy and De Guio 2011; Crozier 2020; Cherp et al. 2021). Indeed, it is not until growth has reached its maximum speed (the steepest part of an S-curve trajectory) that robust projections for future growth can be made with more confidence (Cherp et al. 2021). Even then, additional assumptions must be made about the shape of the S-curve and the saturation point at which growth rates stabilize. For example, whether deceleration at the end of the S-curve mirrors the acceleration at the beginning significantly impacts the speed at which a technology reaches full saturation. Yet no S-curve in the real world is perfectly symmetric, and new evidence from past transitions suggests that S-curves can be highly asymmetric (Cherp et al. 2021). Technologies can also

encounter obstacles as they diffuse, such as supply chain constraints, that alter or limit the shape of the growth, but these challenges are similarly difficult to anticipate.

Identifying enabling conditions for climate change mitigation

To support global efforts to achieve 1.5°C-aligned targets for 2030 and 2050, each *State of Climate Action* report identifies enabling conditions that can help overcome barriers to transformational change. To inform our selection, we first review the academic literature on transition, transformation, and systems change theory as it relates to global environmental change research. We also assess case studies of historical transitions of socio-technical systems (e.g., power, transport, and industry) and transformations of social-ecological systems (e.g., management of forests and wetlands). Although the specific factors supporting systems change range widely across the literature, we identify several common enabling conditions, including innovations, regulations and incentives, strong institutions, leadership from key change agents, and shifts in behavior and social norms (Table 1). While we present these categories of enabling conditions as discrete from one another, we also recognize that, in reality, these supportive measures may fall into more than one category.

Exogenous changes, including both shocks (e.g., economic recessions, conflicts, or pandemics) and slower-onset events (e.g., demographic shifts), can also create windows of opportunity for transformation by destabilizing existing systems. These external forces, for example, can focus public attention on reducing previously unseen risks, motivate policymakers to adopt niche innovations to address new crises, or create space for leaders who support transforming existing systems to win elections. However, such shocks can also spur backlash against change, further entrenching existing systems. Given that such crises are often immediate, unforeseen, and disruptive, we exclude them from our assessment of underlying conditions that enable climate change mitigation.

After determining a common set of factors supporting systems change, we then synthesize the academic literature, as well as peer-reviewed, well-cited papers published by independent research institutions, UN agencies, and high-level sectoral coalitions (e.g., the Energy Transitions Commission and the High Level Panel for a Sustainable Ocean Economy) to identify critical barriers to transformational change within each system, as well as key enabling conditions across these five overarching categories that may help decision-makers surmount such obstacles to achieve 2030 and 2050 targets aligned with holding global warming to 1.5°C. We select enabling conditions that can support climate mitigation, specifically; however, if implemented these measures may have wide-ranging impacts, for example on biodiversity, equity, and human health. Although we do not systematically evaluate these effects for each enabling condition included in this report, we do provide illustrative examples of instances in which these measures can help or hinder efforts to protect nature, reduce inequalities, or improve other sustainable development outcomes. These descriptions are not meant to be comprehensive; rather, they provide a sample of the types of actions needed, as well as trade-offs that must be managed or co-benefits that can be amplified.

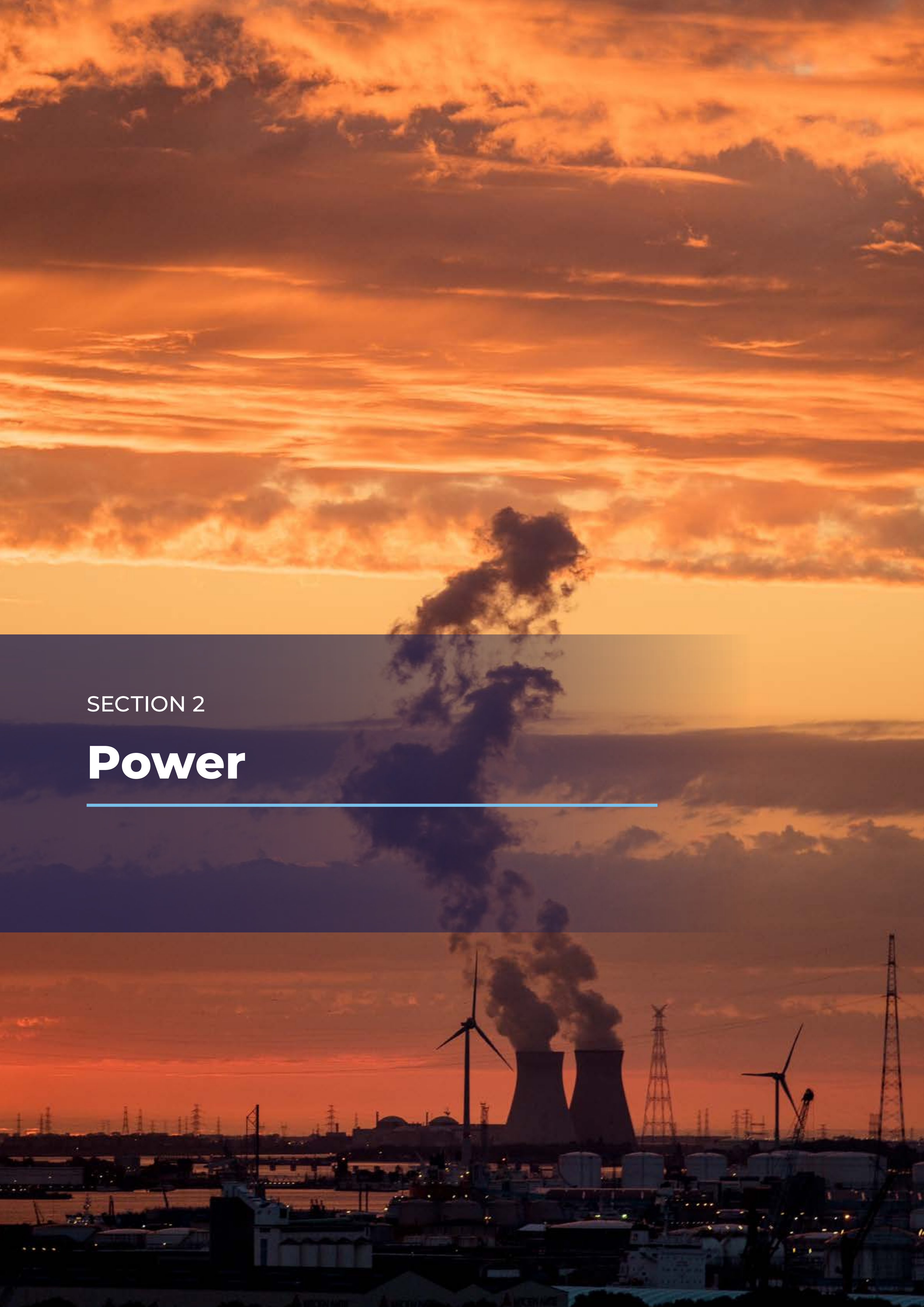
TABLE 1 | Enabling conditions of climate action

CATEGORIES OF ENABLING CONDITIONS	EXAMPLES OF SPECIFIC ENABLING CONDITIONS	DESCRIPTION
Innovations in technology, practices, and approaches	Development and adoption of complementary technologies	Innovations, which broadly encompass new technologies, practices, and approaches, often offer solutions to seemingly intractable challenges. Investments in research and development, support for research networks and consortiums, and universal access to education provide a strong foundation for innovation. Similarly, creating protected spaces for experimentation, pilot projects, and small-scale demonstrations facilitates learning that can lead to improvements in performance and reductions in cost. Developing complementary technologies (e.g., batteries and charging infrastructure for electric vehicles) can also boost functionality and support widespread adoption of innovations.
	Investments in research and development	
	Research networks and consortiums	
	Education, knowledge sharing, and capacity building	
	Experimentation, pilot projects, demonstrations, and other early application niches	
Regulations and incentives	Economic incentives, such as subsidies and public procurement; economic disincentives, such as subsidies reform, taxes, and financial penalties	By establishing standards, quotas, bans, or other "command-and-control" regulations, governments can not only mandate specific changes but also create a stable regulatory environment, often cited as a prerequisite for private sector decarbonization. Using noneconomic or market-based instruments to create incentives (or disincentives) can also shape action from companies, nonprofit organizations, and individuals—and, in some contexts, may be more politically feasible than command-and-control regulations. For subsidies in particular, revenues must be raised to cover these costs, and the mechanisms to do so will also vary by system and region.
	Noneconomic incentives, including removal of bureaucratic hurdles, measures that spotlight good or bad behavior to influence reputations, transitional support to affected communities, or transferring ownership of natural resources to local communities	
	Quotas, bans, regulations, and performance standards	
Strong institutions	Establishment of international conventions, agreements, and institutions	Establishing new institutions or strengthening existing ones can ensure that the policies designed to reduce greenhouse gas emissions are effectively implemented. These institutions can enforce laws, monitor compliance with regulations, and penalize those who break the rules. Creating more transparent, participatory decision-making processes at all levels of government can also help reconfigure unequal power dynamics and enable marginalized communities—those who have often suffered from business-as-usual actions and who generally have the most to gain from transitions to new systems—to steer transformations to a net-zero future.
	Creation of national ministries, agencies, or interagency taskforces	
	Changes in governance, such as more participatory, transparent decision-making processes or natural resource management	
	Efforts to strengthen existing institutions by, for example, increasing staff, funds, or technological resources	
Leadership from change agents	Leadership from national and subnational policymakers, such as setting ambitious targets	Successful transitions often depend on sustained, engaged leadership from a wide range of actors who envision new futures, develop roadmaps for change, initiate actions, and build coalitions of those willing to help implement these plans. While these champions may lead governments, companies, and nonprofit organizations, they need not always sit at the helm of an institution. Civil society organizations, as well as social movements, can effectively pressure those in power to accelerate transitions, and beneficiaries of these changes play an important role in resisting attempts to return to business as usual. Diverse, multistakeholder coalitions that bring these champions together can be a powerful force for change, unifying disparate efforts, pooling resources, and counterbalancing well-organized, influential incumbents.
	Leadership from the private sector, such as establishing ambitious climate commitments and adopting good practices to implement them	
	Diverse, multistakeholder coalitions	
	Beneficiaries of transitions	
	Civil society movements	
Behavior change and shifts in social norms	Changes in behavior	Through educational initiatives, public awareness campaigns, information disclosure, or targeted stakeholder engagement, agents of change can make a clear, compelling case for transitions, explain the consequences of inaction, and identify concrete steps that individuals can take to help collectively accelerate transitions. They can build consensus for a shared vision of the future, as well as prime people for behavior change interventions. As social norms begin to shift, so too will the policies communities support, the goods and services they demand, and their consumption patterns.
	Shifts in social norms and cultural values	

Sources: Enabling conditions were identified from a synthesis of the following studies: Chapin et al. (2010); Few et al. (2017); Folke et al. (2010); Geels et al. (2017); Geels and Schot (2007); Hölscher et al. (2018); ICAT (2020); Levin et al. (2012); Moore et al. (2014); Olsson et al. (2004); Otto et al. (2020); O'Brien and Sygna (2013); Patterson et al. (2017); Reyers et al. (2018); Sharpe and Lenton (2021); Sterl et al. (2017); Victor et al. (2019); Westley et al. (2011); Levin et al. (2020); Bergek et al. (2008); Hekkert et al. (2007).

SECTION 2

Power



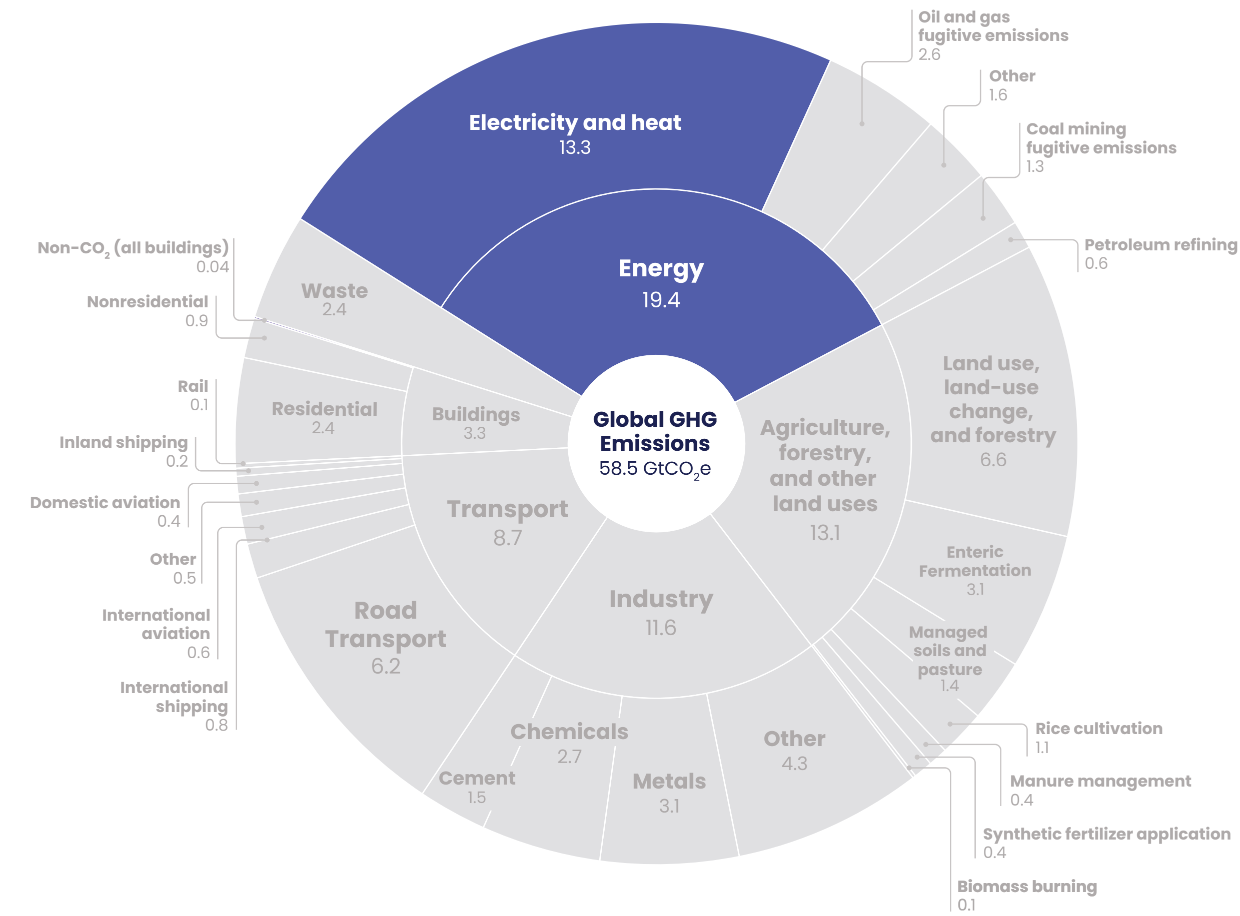
Limiting global temperature rise to 1.5°C depends on rapidly transforming the world's power system. Electricity generation accounts for around 23 percent of global greenhouse gas emissions and remains the single-largest source of CO_2 emissions globally (Figure 2) (Minx et al. 2021; 2022). Decarbonizing the power sector is made more urgent by the fact that global energy demands are rising and decarbonization pathways across other sectors (e.g., buildings and transport) will rely on zero-carbon[10] electricity. Globally, around 733 million people (10 percent of the world population) did not have access to electricity in 2020 (World Bank 2022c), with many using firewood to meet their most basic energy needs. It is crucial we improve their access to energy with zero-carbon power sources.

Over the last two decades, carbon dioxide emissions from electricity production have increased by 0.25 gigatonnes of carbon dioxide ($GtCO_2$) each year (Figure 3). While emissions contracted by around 3.1 percent in 2020, primarily due to the COVID-19 pandemic, they rebounded to a record high in 2021 (IEA 2022c). The GHG footprint of the power sector is higher still when including methane emitted from oil and gas operations for electricity generation.

Emissions from the power sector can primarily be attributed to the use of two fuels: coal and fossil gas.[11] Gas generation contributes around 22 percent of total emissions due to electricity generation, while coal emits significantly more, at around 75 percent (IPCC 2022b). Worryingly, these two fuels dominate the global power sector and their use is increasing globally.

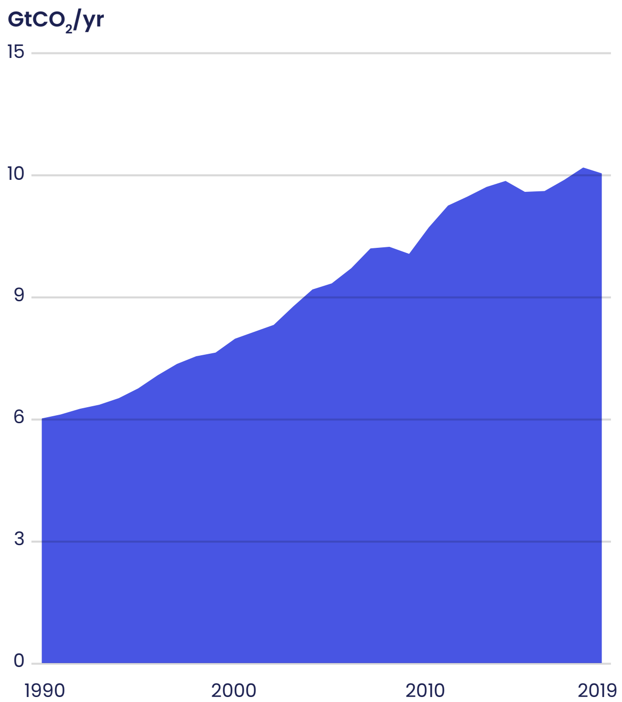
Even so, there are encouraging signs, and the power sector is showing major transformations. The cost of renewable energy and storage technologies have

FIGURE 2 | Power's contribution to global GHG emissions in 2019



Notes: CO_2 = carbon dioxide; GHG = greenhouse gas; $GtCO_2e$ = gigatonnes of carbon dioxide equivalent.
Source: Minx et al. (2022), described in Minx et al. (2021) and used in IPCC (2022b).

FIGURE 3 | Global CO_2 emissions from power



Notes: CO_2 = carbon dioxide; $GtCO_2$/yr = gigatonnes of carbon dioxide per year.
Sources: IEA (2021r, 2022c).

continued to plummet at unprecedented rates, leading to record-breaking growth in adoption of these technologies in 2021 (IRENA 2022a). Between 2015 and 2019, the share of zero-carbon technologies in the global electricity generation mix rose by as much as 21 percent. Meanwhile, green hydrogen is beginning to emerge within international energy policy priorities. While the importance of these trends cannot be overstated, it is widely recognized that a much faster energy transition is needed still (IPCC 2022b).

Major shifts are urgently needed in the power sector: energy access gaps need to be closed; energy needs to be used more efficiently, while demands need to be electrified and (in advanced economies) reduced; fossil fuels need to be phased out; and zero-carbon power and energy storage needs to be prioritized in energy policy. These shifts will be key to ensuring that global warming is limited to 1.5°C. Yet changes must occur in a manner that is equitable and sustainable. Historically, a handful of countries in the developed world have emitted the vast portion of emissions. These nations will need to lead the way in delivering the clean energy transition, while helping developing countries leapfrog to a zero-carbon power system, circumventing economic development that is underpinned by fossil fuels.

TABLE 2 | Summary of global progress toward power targets

INDICATOR	MOST RECENT DATA POINT (YEAR)[a]	2030 TARGET	2050 TARGET	TRAJECTORY OF CHANGE	ACCELERATION FACTOR	STATUS
Carbon intensity of electricity generation (gCO_2/kWh)	450 (2019)[b]	50–125	5–25 (2040) <0[c] (2050)		5x	
Share of zero-carbon sources in electricity generation (%)	36 (2019)[b]	74–92	87–100 (2040) 98–100 (2050)		6x	[d]
Share of unabated coal in electricity generation (%)	37 (2019)[b]	0–2.5	0 (2040) 0 (2050)		6x	
Share of unabated fossil gas in electricity generation (%)	24 (2019)[b]	17	5 (2040) 0 (2050)		N/A; U-turn needed	

Notes: gCO_2/kWh = grams of carbon dioxide per kilowatt-hour.

[a] This data analysis is based on historical data collected before the IEA's recent most data update, and 2018 was the last available historical year at the time this analysis was conducted. The text might refer to newer historical data.

[b] Data for these indicators are not publicly available and were accessed with paid licenses to datasets or with permission from the data provider.

[c] Achieving below zero-carbon intensity implies biomass power generation with carbon capture and storage. Our targets limit bioenergy with carbon capture and storage use to 5 GtCO2 per year in 2050. See Schumer et al. for further information about our sustainability criteria.

[d] The category of progress was adjusted for indicators categorized as exponential change likely, using methods outlined in this report's companion technical note (Schumer et al. 2022), and so in these instances, the category of progress identified does not always match the acceleration factor calculated using a linear trendline.

Sources: Historical data from IEA (2021r); targets from Climate Action Tracker (2020b).

This section examines the progress of the global power sector transition by analyzing four indicators related to electricity generation: (1) carbon intensity of electricity generation; (2) share of zero-carbon sources of electricity generation; (3) share of unabated[12] coal; and (4) share of unabated fossil gas (Table 2). The first three indicators show change is heading in the right direction but at an insufficient rate, while the share of fossil gas generation is heading in the wrong direction.

Status of power indicators

POWER INDICATOR 1:

Carbon intensity of electricity generation (gCO_2/kWh)

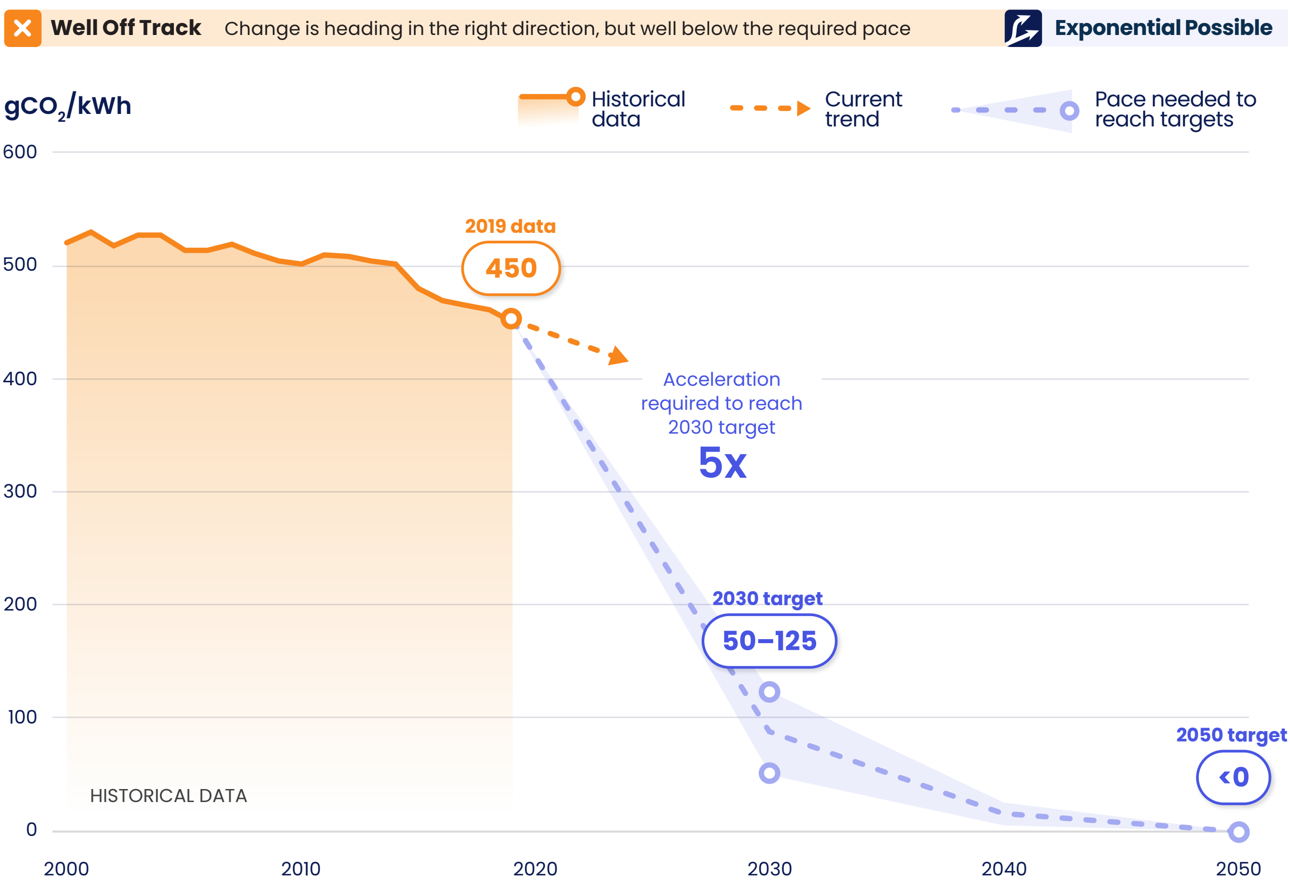
- **Target**: The carbon intensity of electricity generation globally falls to 50–125 grams of carbon dioxide per kilowatt-hour (gCO_2/kWh) in 2030 and to below zero in 2050.

Monitoring the carbon intensity of power generation is an effective measure of progress toward the main goal for the sector: reaching net-zero emissions. It provides an understanding of CO_2 emissions per unit of electricity based on changes in power sources and efficiency, without distortion from system-level changes such as additional capacity and increasing demand. However, alongside this metric it is important to keep tracking absolute emissions (Figure 3), given that carbon intensity can decrease while total emissions increase if electricity demand is large enough.

Between 1990 and 2011, global power sector carbon intensity fluctuated slightly, but it remained around 520 gCO_2/kWh. After 2011, it has gradually declined, though not at a sufficient pace to be 1.5°C-aligned (Figure 4). A steep decline in coal power generation during the COVID pandemic caused the carbon intensity of electricity generation to fall by 3 percent between 2019 and 2020 (IEA 2021n). Yet it is estimated that a strong rebound in coal power generation in 2021 will push this indicator higher once more, highlighting the need to rapidly phase out unabated coal from the global power system.

While this indicator is heading in the right direction, it is currently well off track. The rate at which the carbon intensity of the power sector has declined over the past five years needs to accelerate by almost five times to meet the 2030 target. If the share of zero-carbon electricity generation grows rapidly, progress on the carbon

FIGURE 4 | Historical progress toward 2030 and 2050 targets for carbon intensity of electricity generation



Notes: gCO_2/kWh = grams of carbon dioxide per kilowatt-hour. Data for 2021 are an estimate for now; 2020 data will be added when available.

Sources: Historical data from IEA (2021r), computed using the "GHG emissions from fuel combustion" data product in accordance with the associated IEA license agreement; targets from Climate Action Tracker (2020b).

intensity of electricity generation may occur faster than projected (Way et al. 2021), potentially improving this indicator toward being on track.

POWER INDICATOR 2:
Share of zero-carbon sources in electricity generation (%)

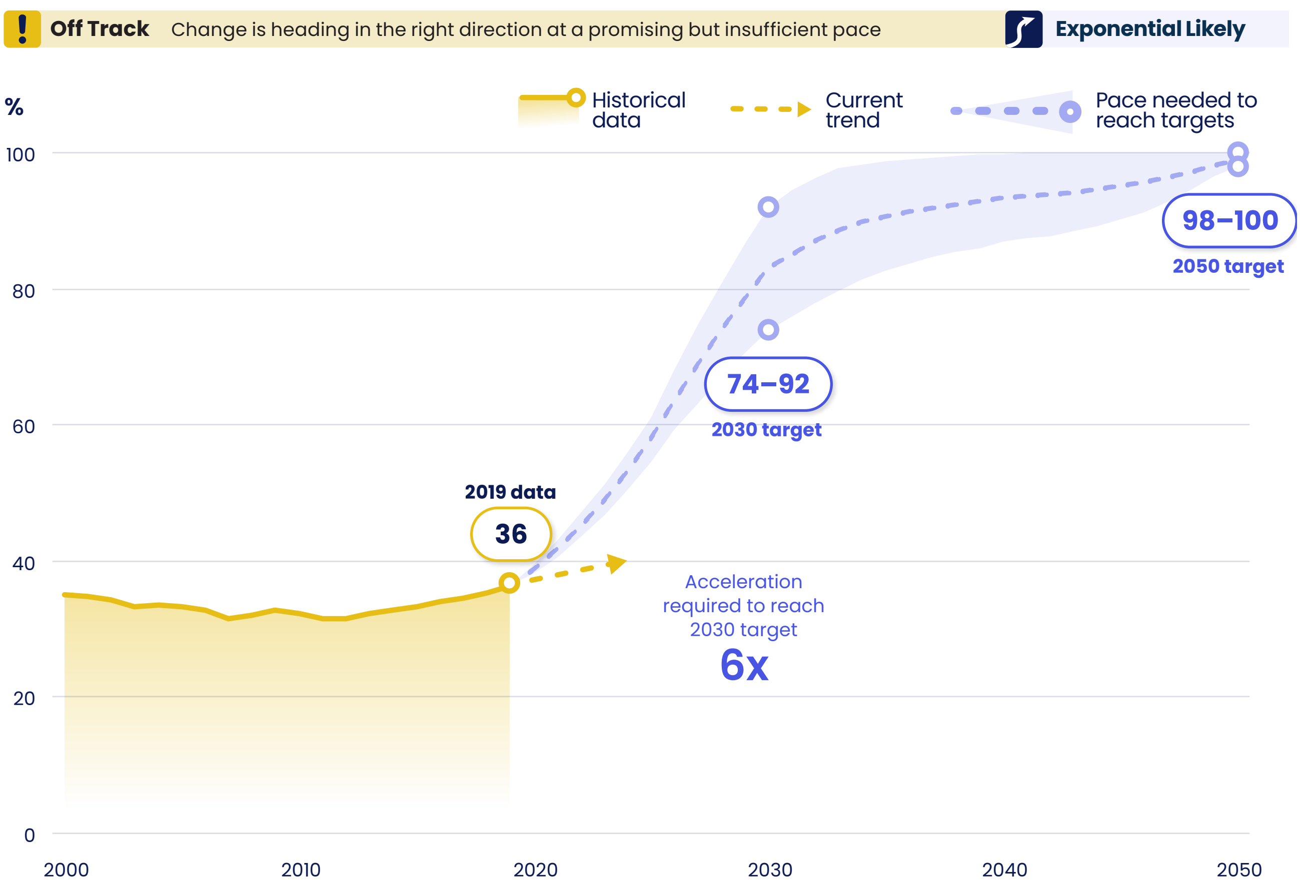
- **Target**: The share of zero-carbon sources[13] in electricity generation reaches 74-92 percent by 2030 and 98-100 percent by 2050.

The growth of zero-carbon power technologies will play a critical role in decarbonizing the power system, particularly the scale-up of wind and solar, which need to be prioritized in power sector build-outs globally (IPCC 2022b). More specifically, these zero-carbon power sources include solar, wind, hydropower, biomass, nuclear, geothermal, and marine technologies. Adoption of any of these technologies entails trade-offs. Generating power from biomass, for example, is not inherently zero-carbon and requires adequate safeguards. Further, the pathways assessed in this report limit biomass-fired electricity to under 8,000 terawatt-hours (TWh) electric (see Schumer et al. 2022 for more information on how these trade-offs were managed).

The share of zero-carbon power has shown almost no net change between 2000 (35.2 percent) and 2019 (36.4 percent) (Figure 5). This is because the growth in zero-carbon power has been matched by the growth in total generation. Out of all zero-carbon power sources, hydropower contributed the largest share of total electricity generation, at 16 percent (4,290 TWh) in 2019. Despite nuclear power output having plateaued since 2006 (World Nuclear Association 2022), it maintained its place as the second-largest zero-carbon contributor to total generation at around 10 percent (2,790 TWh). Solar and wind are the fastest-growing sources of electricity generation (IRENA 2022a) and together accounted for 8 percent of total generation (2,232 TWh). Meanwhile, all other zero-carbon sources, including bioenergy, accounted for 2 percent of total generation (720 TWh).

The share of zero-carbon power is currently growing too slowly to reach 74–92 percent by 2030, a target that would align the power sector with 1.5°C-compatible pathways (Figure 5). The rate of progress made in increasing

FIGURE 5 | Historical progress toward 2030 and 2050 targets for share of zero-carbon sources in electricity generation



Note: Zero-carbon sources include solar, wind, hydropower, geothermal, nuclear, marine, and biomass technologies. Also, the category of progress was adjusted for this indicator, which we categorized as exponential change likely, using methods outlined in Schumer et al. (2022). So in this instance, the category of progress identified does not match the acceleration factor calculated using a linear trendline.

Sources: Historical data from IEA (2021r), computed using the "World Energy Balance" data product in accordance with the associated IEA license agreement; targets from Climate Action Tracker (2020b).

the share of zero-carbon power needs to be nearly six times faster than it has been the past five years to reach the 2030 target. However, the share of zero-carbon power is likely to follow an S-curve and the technology is in the breakthrough stage of adoption, so the rate of change will likely accelerate faster than the past five years, although this is not guaranteed. Based on purely linear growth this indicator would be "well off track," but given our assessment of the literature and consultations with experts, which suggest that zero-carbon power sources are approaching a tipping point as they become cheaper than fossil fuels and thus could grow in a nonlinear fashion, we upgrade the category to "off track."

A number of interventions could bring this indicator on track. The deployment of solar and wind infrastructure should be sped up. These two technologies are widely expected to form the backbone of the future electricity system (IPCC 2022b), and their output accounts for the majority of total generation by 2030 under most Paris Agreement–compatible scenarios for the power sector (e.g., IEA 2021h; Way et al. 2021; Climate Action Tracker 2020c; Ember 2022). Indeed, wind and solar generation has been growing in a nonlinear fashion for decades and is likely to grow until it dominates, following an S-curve trajectory (Jaeger 2021). The question remains whether the shares of wind and solar in total generation can grow at a sufficient rate—at around 20 percent per year (Ember 2022)—to meet 1.5°C-aligned targets. A recent study found that in countries where solar and wind generation growth has reached the steepest part of the S-curve, the average maximum rate of growth has still not been enough to meet 1.5°C-compatible targets (Cherp et al. 2021).

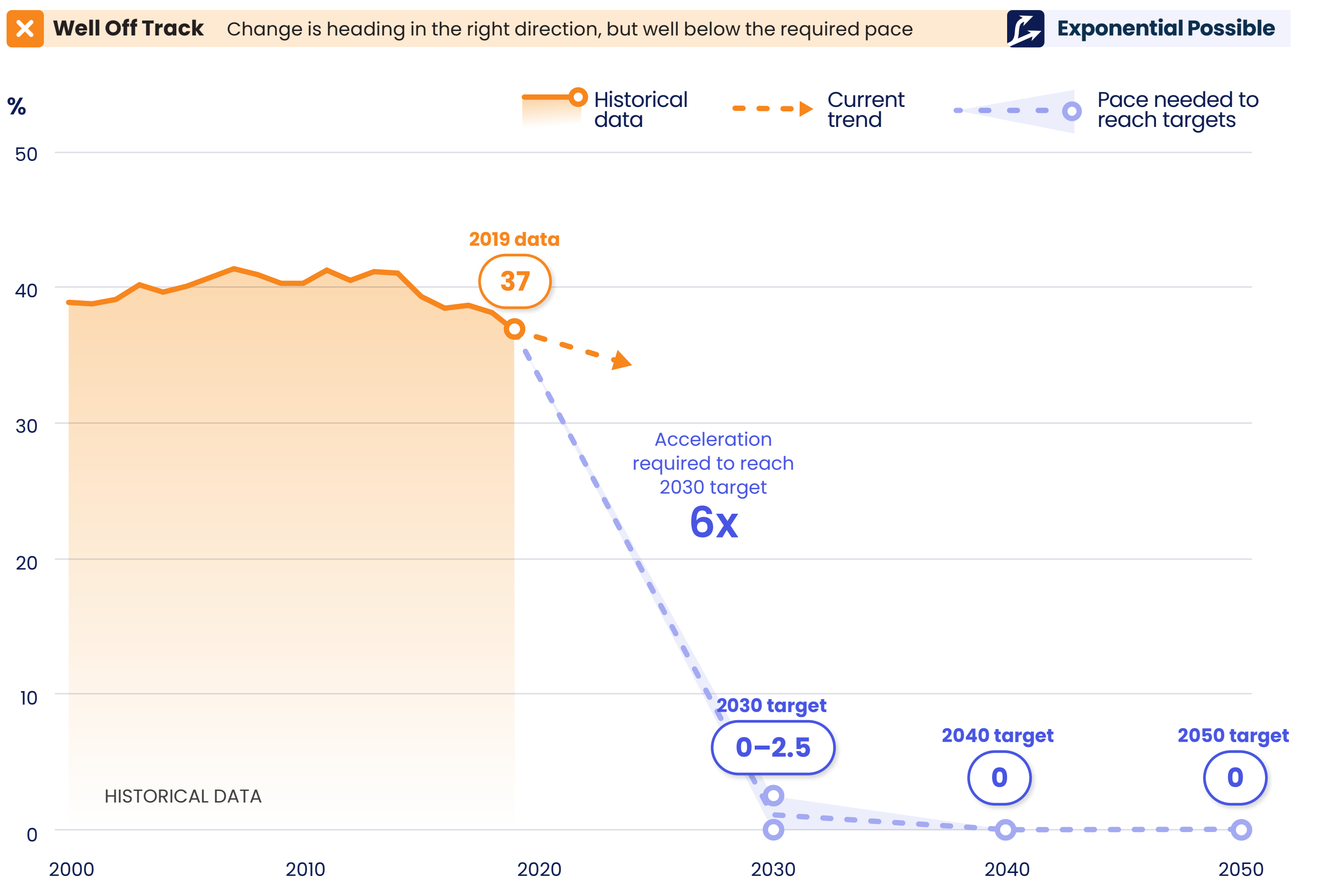
The share of zero-carbon power in generation may experience some form of nonlinear, rapid growth in the coming decades, particularly as solar, wind, and storage technologies continue to decline in costs. However, achieving such dramatic increases in zero-carbon power will require decision-makers to make tough decisions by supporting clean energy while phasing out coal and fossil gas (Indicators 3 and 4).

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

- **Target**: The share of unabated coal in electricity generation falls to 0-2.5 percent by 2030, then to 0 percent by 2040, and remains at 0 percent in 2050.

Coal contributes around three-quarters of power sector CO_2 emissions (IEA 2020f). As shown in Figure 6, the share of unabated coal in electricity generation increased

FIGURE 6 | Historical progress toward 2030 and 2050 targets for share of unabated coal in electricity generation



Note: "Unabated coal" refers to the consumption of coal resources without measures to abate associated carbon dioxide emissions with carbon capture and storage.

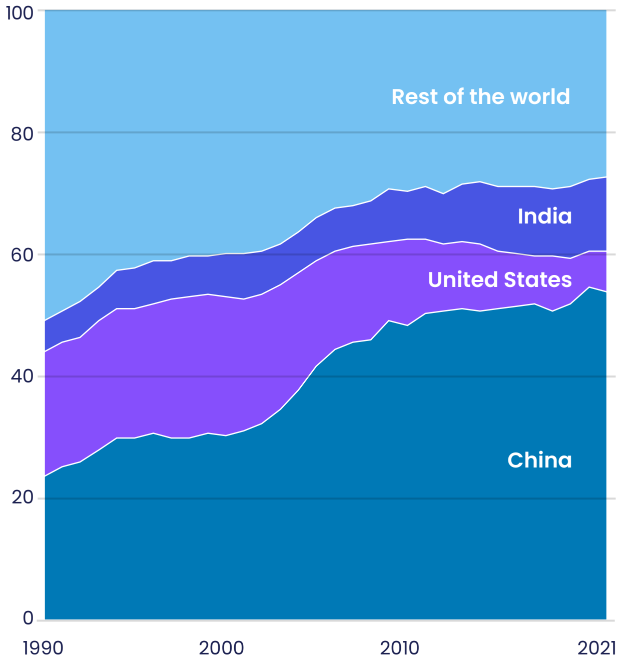
Sources: Historical data from IEA (2021r), computed using the "World Energy Balance" data product in accordance with the associated IEA license agreement; targets from Climate Action Tracker (2020b).

from 39 percent in 2000 to 41 percent in 2007, but it has since been gradually declining. As of 2019, coal shares in electricity generation stood at 37 percent. Estimates from 2020 show that coal generation declined most steeply (–4.4 percent) when compared with all other supply sources, but it later rebounded strongly in 2021.

This rise in demand in 2021 was primarily led by China, where coal consumption has been increasing sharply since 1990 (Figure 7) and now represents over half of the world's demand (5,383 TWh) (BP 2021). A contributing factor to the recent uptick in China's coal use was a substantial loss in hydropower generation due to record-low rainfalls and regional droughts, causing widespread blackouts. Coal usage has also been increasing in India, which is now the second-largest consumer of coal, at around 12 percent of global demand (1,250 TWh). The United States remains the third-largest coal user (6 percent or 899 TWh), but its consumption has been declining since 2008.

Overall, this indicator is heading in the right direction, but it is well off track for reaching the 2030 target (Figure 6), which is critical to aligning the power sector with 1.5°C compatibility. The rate of progress in the decline of coal needs to be almost six times faster than it has been over the past five years to achieve the 2030 target. Significant policy interventions are urgently needed to speed up the pace of change. If zero-carbon power scales up exponentially, the share of unabated coal may fall in turn, but coal will need to be addressed on its own as well.

FIGURE 7 | Coal consumption in China, United States, India, and the rest of the world



Source: Data from BP (2021) via *Our World in Data.*

Planned new coal capacity in regions such as Africa and South and East Asia will need to be halted immediately, and existing coal plants may need to be retired earlier than planned if such a decline is to happen. In member nations of the Organisation for Economic Co-operation and Development (OECD), coal needs to be phased out entirely by 2030, and all coal-fired power stations must be shut down by 2040 at the latest (Climate Analytics 2019).

Globally, around 500 gigawatts (GW) of new coal-fired power stations are in the pipeline, equivalent to 25 percent of existing capacity. The majority of new coal projects are planned for developing regions, often in areas where the main challenge is to provide people with basic energy services around the clock. Here, if policymakers and electricity providers are to prioritize zero-carbon power projects instead of coal, advanced economies will need to make a much greater effort to mobilize climate finance (discussed more in Section 9).

POWER INDICATOR 4:

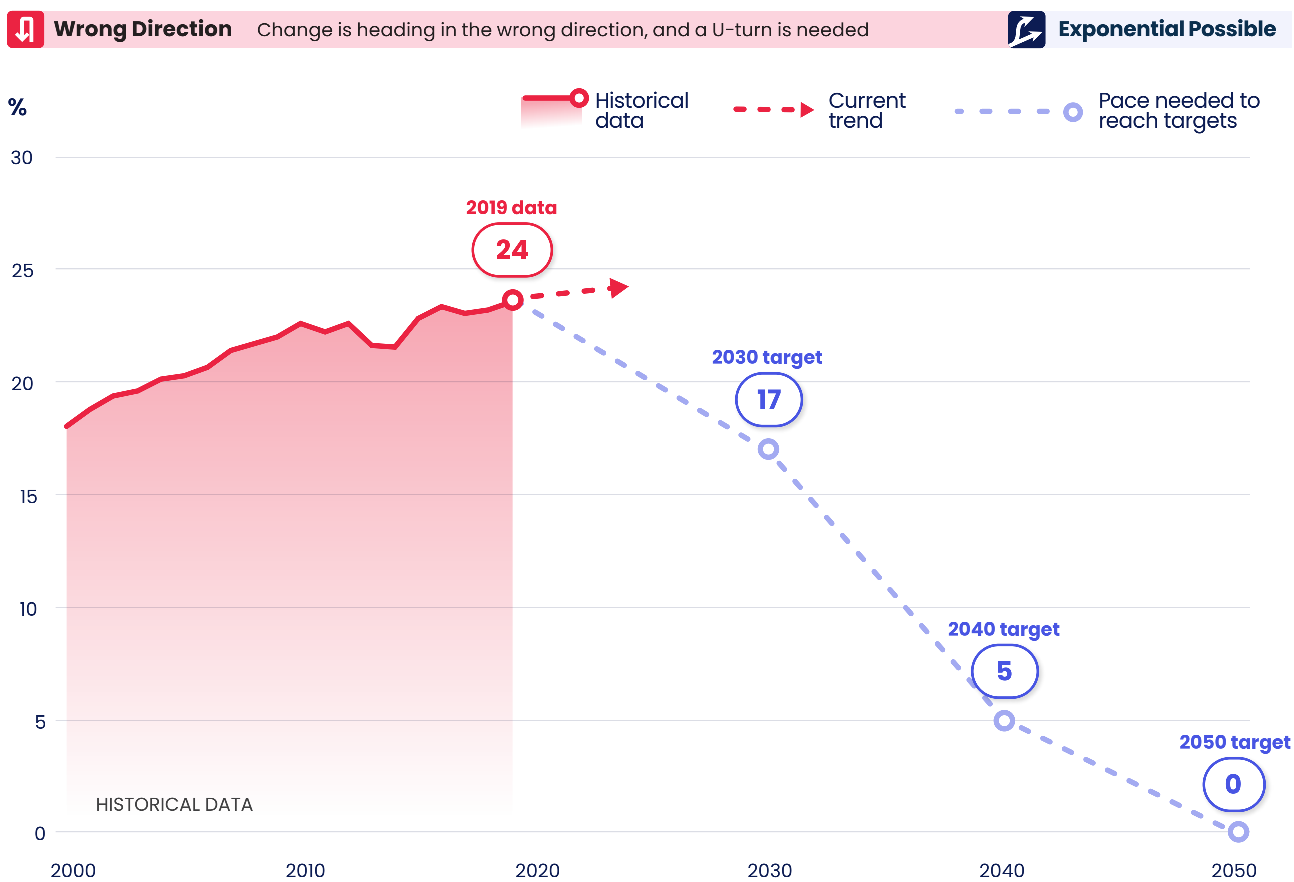
Share of unabated fossil gas in electricity generation (%)

- **Target**: The share of unabated fossil gas in electricity generation falls to 17 percent in 2030, 5 percent in 2040, and then to 0 percent in 2050.

The burning of fossil gas for electricity generation contributes around 22 percent of total power sector emissions (IEA 2021f), and it represents the fastest-growing source of emissions from the sector. As shown in Figure 8, the share of unabated fossil gas grew from 18 percent to 24 percent of total electricity generation between 2000 and 2019. As such, this indicator is heading in the wrong direction, and a reversal in trends is needed to keep the ambitions of limiting warming to 1.5°C alive. Globally, gas shares will need to fall to 17 percent by 2030, 5 percent by 2040, and be completely phased out by 2050.

Generation from fossil gas has been rising swiftly across the world since 1990 (Figure 9), and while the COVID-19 pandemic led to a temporary contraction

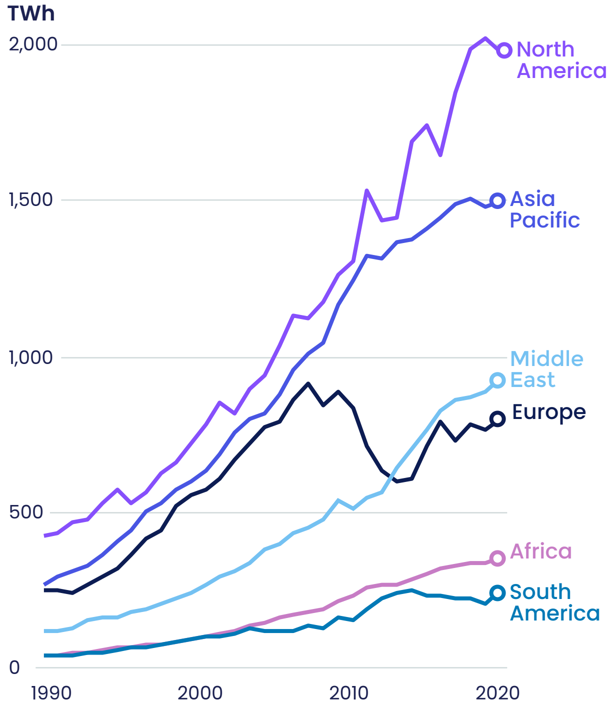
FIGURE 8 | Historical progress toward 2030 and 2050 targets for share of unabated fossil gas in electricity generation



Note: "Unabated fossil gas" refers to the consumption of gas resources without measures to abate associated carbon dioxide emissions with carbon capture and storage.

Sources: Historical data from IEA (2021r), computed using the "World Energy Balance" data product in accordance with the associated IEA license agreement; targets from Climate Action Tracker (2020b).

FIGURE 9 | Electricity generation from gas by region



Note: TWh = terawatt-hour.

Source: Data from BP (2021) via *Our World in Data*.

of demand in 2020, it rebounded in 2021. Fossil gas–generated power in the United States dwarfs almost all other regions at 1,575 TWh as of 2021, followed by Russia (500 TWh), Japan (310 TWh), and China (267 TWh). Indeed, forecasters predict strong growth in demand for fossil gas in the near future, primarily in emerging economies but also in developed regions (e.g., Europe and the United States), in part due to the war in Ukraine (BNEF 2022c).

The notion of fossil gas as a "transition" or even "green" fuel is present in national energy policy. For example, the European Union has recently classified fossil gas as a "green" source of energy under its investment taxonomy, although with some limitations (European Commission 2022b). This is despite fossil gas contributing nearly 50 percent of the recent growth in global fossil carbon emissions (IEA 2021f). The developments of fossil gas resources is worrying as it could lead to carbon lock-in and stranded assets, as well as hinder the development of zero-carbon energy (Gürsan and de Gooyert 2021; Yang et al. 2022). This decision by the European Union undermines its credentials as a climate leader on the world stage. A significant disruption in decarbonization policy would be needed to reverse this narrative.

Global assessment of progress for power

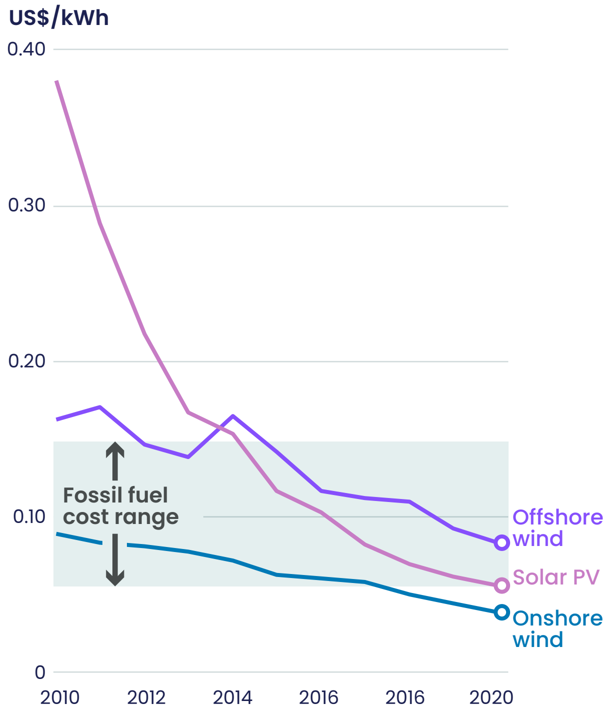
Analyzing the power sector's progress paints a stark picture: fossil fuels continue to dominate the power system and positive tides of change, while encouraging, are not moving at anywhere near the speed necessary to fully decarbonize the sector. Given the power sector's large carbon footprint, as well as its role in decarbonizing other sectors (e.g., transport and buildings), the prospect of limiting global warming to 1.5°C could be pushed out of reach unless the scale and speed of change is accelerated dramatically. Specifically, the patterns in fossil gas consumption need to make a U-turn, coal phaseouts need to happen faster, and the adoption of zero-carbon technologies (wind and solar in particular) needs to keep growing sharply.

There are signs of progress in the power system that invite optimism. Despite the global situation, zero-carbon power has continued to increase around the world. Between 2019 and 2021, generation of zero-carbon technologies has grown: solar by 329 TWh (+47 percent), wind by 441 TWh (+31 percent), hydropower by 42 TWh (+1 percent), nuclear by 4 TWh (+0.14 percent), and other renewables, including bioenergy, by 88 TWh (+13 percent). Meanwhile, the costs of solar and wind continued to plummet beyond expectations. The average levelized cost of energy of solar photovoltaics (PV) fell 7 percent from 2020 to 2021, while offshore and onshore wind fell by 9 percent and 13 percent, respectively (IRENA 2021b). Over the course of the past decade, costs have declined 85 percent for solar, 48 percent for offshore wind, and 56 percent for onshore wind (Figure 10). Battery storage prices have also fallen substantially, by around 89 percent between 2010 and 2021 (Figure 11).

In many regions, renewable technologies have been competing against or even undercutting fossil fuel generation (IRENA 2021b). The continued growth of wind and solar energy, which will be the backbone of the future electricity system, has been driven by a number of factors, including government policy (Figure 12). Public and private sector research and development (R&D) programs have facilitated rapid technological learning and innovation, while support for sustainable energy companies has helped unlock economies of scale. In aggregate, these actions have led to relatively efficient, cheap, and scalable renewable energy technologies. These sorts of actions by governments and businesses must continue and drastically increase to put us on track to achieve the 1.5°C limit.

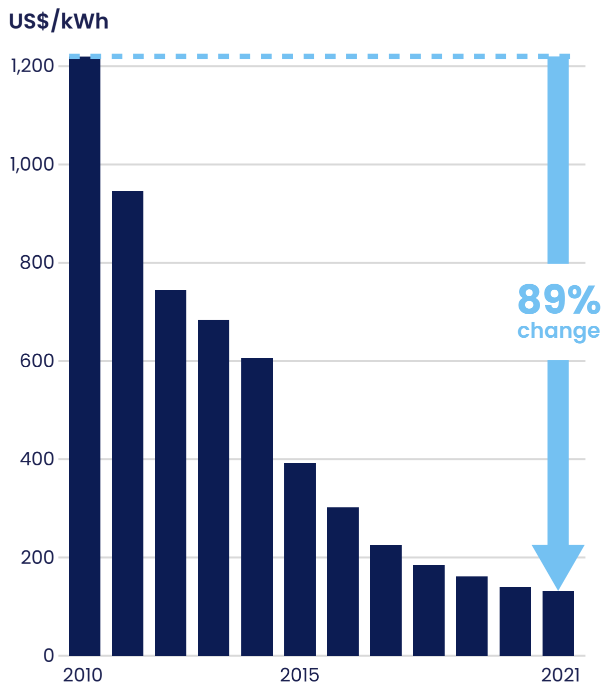
Yet Russia's illegal invasion of Ukraine in 2022 has led to a seismic shift in global energy policy, the effects of which could hamper our ambitions to keep warming below 1.5°C, if left unchecked. As Russia has reduced its energy exports, one of the most concerning trends has

FIGURE 10 | Weighted average levelized cost of electricity for selected renewable energy technologies and fossil fuel comparison



Note: $/kWh = dollars per kilowatt-hour; PV = photovoltaics.
Source: IRENA (2021b).

FIGURE 11 | Lithium-ion battery price trends



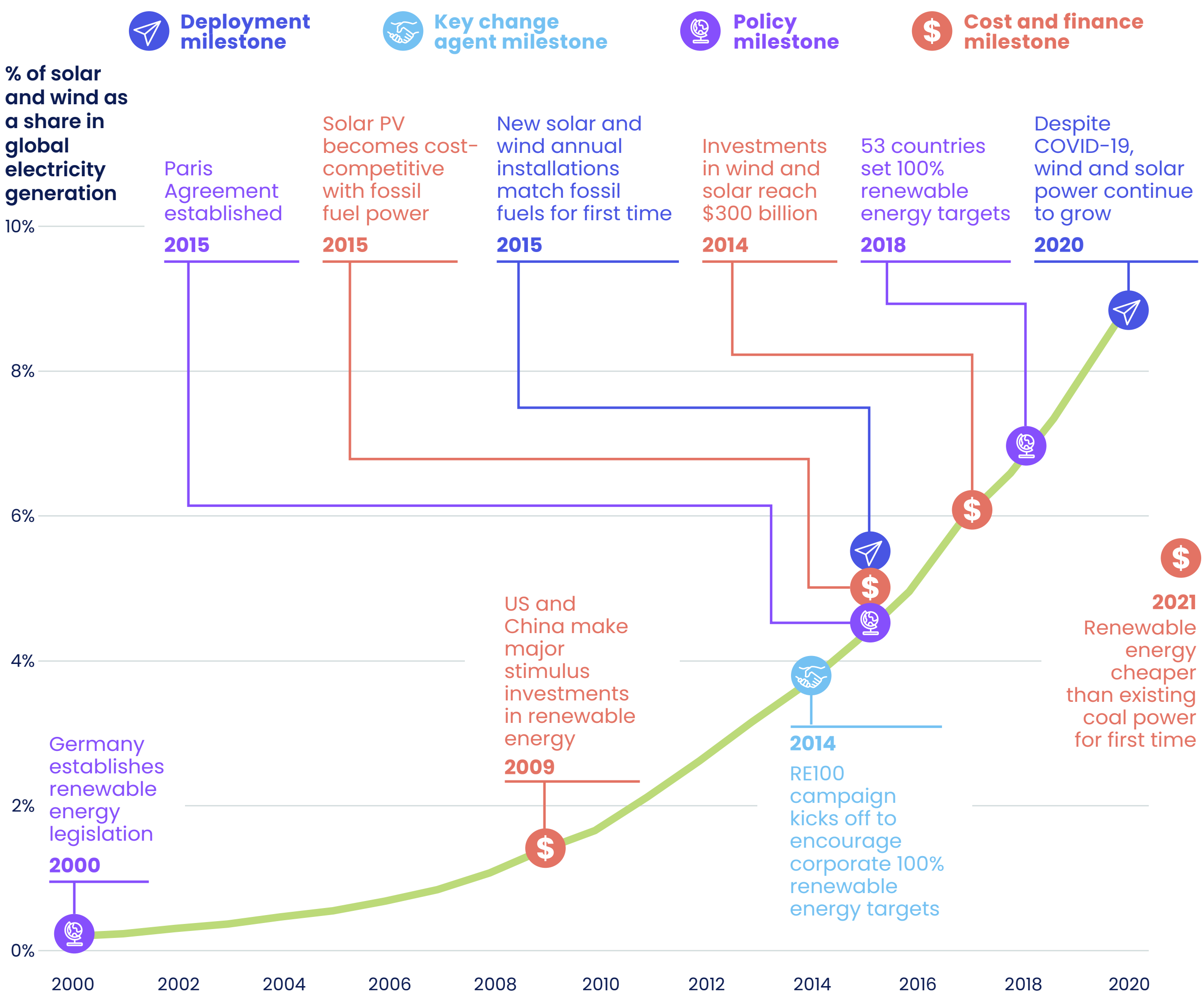
Note: $/kWh = dollars per kilowatt-hour.
Source: BNEF (2022a), reprinted with permission from Bloomberg New Energy Finance.

been the resurgence of coal in European countries,[14] where old plants have been reactivated to stave off the threat of power shortages. The European Union's plan to decrease its long-term dependency on Russian imports by increasing its zero-carbon energy targets to 2030 from 40 percent to 45 percent was a step in the right direction. However, it also plans to ramp up investments in fossil gas terminals, considering these as a "green" investment. Given the European Union's high historical contributions to global emissions, these decisions do not align with 1.5°C pathways for the region. In addition to the inherent risks of carbon lock-in and stranded assets, these trends could well slow down the clean energy transition. Rather than attempting to *shift* its dependency on Russian fossil fuels, the European Union could seek to *reduce* the dependency. This could be done by rolling out demand reduction; energy efficiency and electrification measures; aggressively rolling out zero-carbon infrastructure, in particular solar and wind; and, where appropriate, enhancing the lifetime of its existing zero-carbon nuclear plants.

Even more worrying is that the actions of rich economies such as the European Union in global fossil gas markets have deprived developing countries of energy. As energy prices have ramped up, countries such as Pakistan, Bangladesh, India, and Brazil have been unable to compete to procure fossil gas contracts. This has led to an uptick of coal use in developing nations (BP 2021), for example in China and India. The extant energy crisis risks pushing emerging economies toward coal, which would divert the global power sector away from 1.5°C-compatible pathways. Most of the 500 GW of coal (23 percent of existing global capacity) currently under construction or in the pipeline is in developing nations, and greater financial support is needed from advanced economies to divert countries in Africa and South and Southeast Asia toward zero-carbon energy and away from coal and fossil gas, thus aligning us with 1.5°C pathways.

Zero-carbon energy is now firmly at the heart of national decarbonization policies. As of 2021, at least 182 countries had included renewable energy components in their nationally determined contributions, but the scale of ambition is nowhere near what is needed to limit warming below 1.5°C (IRENA 2022c). Commitments and rhetoric are not sufficient and do not reduce emissions. Governments and businesses must now prioritize delivery. In that sense, developing economies in Asia are emerging as the clear world leaders despite their historically low contribution to global emissions: per capita electricity generation from zero-carbon technologies in China, South Korea, Vietnam, and India is increasing at among the fastest rates globally (BP 2021). China alone is leading the growth in new solar, wind, and nuclear capacity additions.

FIGURE 12 | The exponential growth of solar and wind energy in relation to key milestones



Note: PV = photovoltaics.
Source: Jaeger (2021).

Recent events have also highlighted the challenge of delivering a just and equitable clean energy transition. There have been some notable successes: Spain developed and funded a just transition plan to assist workers displaced by coal phaseouts, while South Africa launched a just transition framework to deal with the anticipated social and economic impacts of the transition. Yet the transition has caused negative impacts in certain areas (e.g., Jolley et al. 2018; Wang and Lo 2022). For example, in Spain, which is seeing a steep increase in renewable energy, new solar and wind plants were built without adequate participation from local stakeholders and environmental impact studies, leading to public backlash against renewable energy projects, aesthetic degradation in areas of natural beauty, and greater stresses on populations of rare species (Hearn and Castaño-Rosa 2021). Moreover, subsidies for household rooftop PV favored rich communities, which exacerbated energy poverty in the country.

Meanwhile, rich countries have come up short again in providing climate finance (see Finance Indicators 1–3), hampering the funding of clean energy projects in developing economies that are so crucially needed to achieve the 1.5°C limit. Developing and emerging countries account for two-thirds of the global population (around 5.3 billion people) and yet only one-fifth of total clean energy investment. This is despite the fact that the average cost for reducing emissions in these countries is roughly half that of developed countries (IEA 2021c). As such, many developing countries, especially in Asia and Africa, have low or unreliable access to electricity (Ritchie et al. 2020b). Switching current levels of power from fossil fuels to zero-carbon sources without increasing electricity access would lead to vastly unequal outcomes. Also, realizing a net-zero power sector in developing and emerging economies without international assistance remains not only doubtful but

also inequitable given that these regions have contributed much less to cumulative carbon emissions (Ritchie et al. 2020a).

Finally, extreme climatic events have demonstrated that the power sector is not only the major contributor to global emissions but also highly vulnerable to climatic change. Water-cooled coal and fossil gas power stations have been forced to close during periods of drought (Byers et al. 2020). Changing temperatures are driving up energy demand (van Ruijven et al. 2019). Coastally sited power stations, which are often fossil-based, are vulnerable to flooding (Koks et al. 2019). Other risks to the power sector from acute and chronic climate events are likely to increase in frequency with climate change (Cronin et al. 2018). And given that power systems are the backbone of societies, these risks have cascaded throughout the economy, causing massive financial and societal losses through disruptions to industry, water, food, and transport systems (Thacker et al. 2017).

Overall, the global power sector is currently grappling with three enormous challenges: the need to decarbonize, the ambition to decrease reliance on Russian oil and gas, and rising costs of fossil fuels. Zero-carbon power is a solution to all three, if delivered rapidly and in a manner that is equitable and just.

Enabling conditions for climate action across power

The transition to a sustainable power sector continues to gather pace as more countries and businesses recognize the benefits. However, there are major barriers: a lack of national ambition to scale up zero-carbon power; powerful vested interests supporting fossil fuels; perceived investment risks in clean energy projects; disadvantageous market conditions that prevent zero-carbon energy projects from coming online; and technical constraints on highly renewable systems. Yet policymakers can promote enabling conditions to overcome these barriers, such as investing in research and development of clean energy technologies, modernizing power grids, and reforming energy markets to remove bureaucratic hurdles.

Set ambitious targets to scale up renewable energy and phase out fossil fuels

One of the main barriers to the clean energy transition is when investors face uncertainty around future energy strategies. National energy policies that continue to rely on fossil fuels or show a lack of ambition to scale up zero-carbon power may promote further investment in fossil fuels (Alova et al. 2021), thus risking carbon lock-in (CREA and Global Energy Monitor 2021; Urgewald 2021).

Key change agents, such as governments, international institutions, and private businesses, can lead in enabling conditions for change. One of the most powerful mechanisms is to set clear and ambitious targets, enshrined in law or institutional policy where possible, to rapidly scale up renewables and phase out fossil fuels. Several key economies have already committed to 1.5°C-aligned coal phaseouts, including the United Kingdom (2024), Germany (2030), and Canada (2030), while there are a number of examples of highly successful and early-set renewable energy targets (see Box 2). Also, some international finance institutions are taking action to phase out fossil fuels. For example, the Asian Development Bank has ceased funding for new coal plants and has allocated financing to retire coal projects early (ADB 2021). Setting strong targets can send a powerful signal throughout the economy, indicating the future direction for travel and giving investors' confidence to back clean energy projects. It is important to recognize that such targets should be equitable, meaning countries will need to phase out fossil fuel generation at different rates, with developed countries having an obligation to achieve coal phaseout earlier than developing nations (Kuramochi et al. 2018).

Integrate renewable energy through storage

Although recent years have witnessed significant innovation in renewable energy technologies, the variability of weather-dependent renewable systems still poses a key barrier. Further investment and innovation will be needed to develop storage systems that can manage variability from decentralized renewable systems in a cost-effective manner, although in some cases it may be more economical to overbuild renewable capacity rather than invest in storage technologies (AEMO 2021a).

Pumped hydropower is playing an increasingly important role in energy storage, but it is not possible in many places due to technical constraints, as well as public opposition to its impact on ecosystems and local populations (Hunt et al. 2020). Battery storage is more promising for expansion and has seen dramatic cost declines (Figure 11), but its scaling is constrained by energy density, capacity, and cost. These constraints will require greater investment in research and development to resolve (Koohi-Fayegh and Rosen 2020). Meanwhile, innovations in storage systems using green hydrogen (manufactured using renewable energy–powered electrolysis) are also vital for sectors that require portable and energy-dense storages over

BOX 2 | A case-study of South Australia's renewable energy targets and sectoral transformation

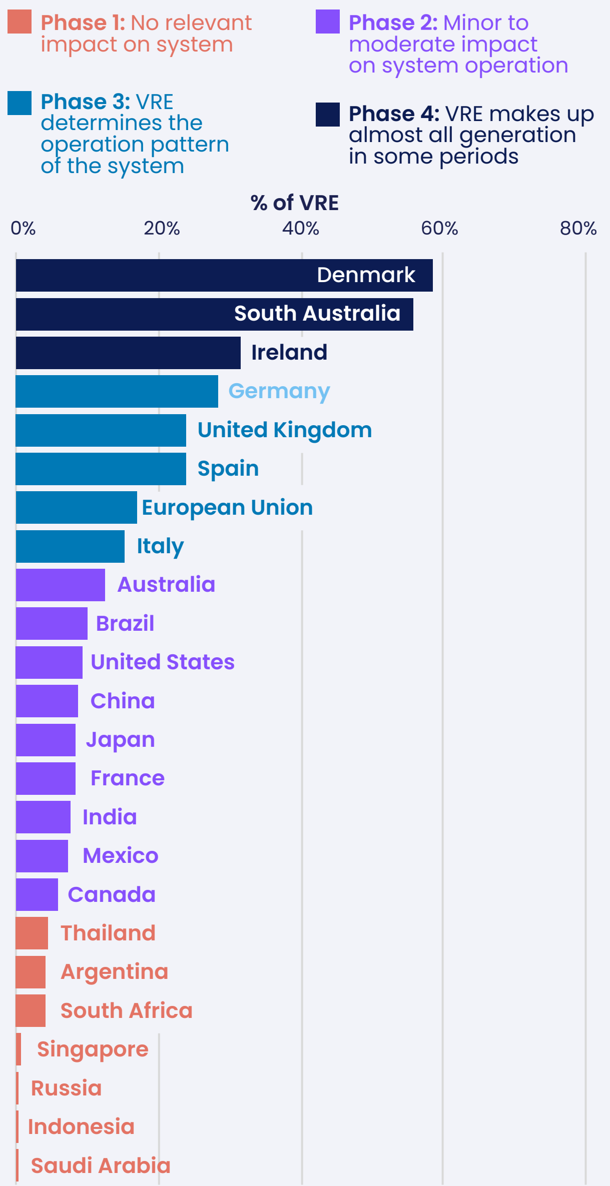
The state of South Australia, with a population of roughly 1.8 million, was completely reliant on fossil fuels for electricity generation until 2006 (OpenNEM 2022). It has since undergone a remarkably rapid renewable energy transformation, reaching 100 percent renewable generation for 180 days in 2021 using solar, wind, and battery storage (Department for Energy and Mining 2022). Playing a key role in this achievement were the early-set, strong, and progressively strengthened renewable energy targets, combined with financial subsidies from the state. These schemes provided regulatory and financial certainty to investors to proceed with the development of projects, secure power purchase agreements, and engage equipment suppliers and contractors. The introduction of streamlined planning regulations for wind farms, such as fast-tracking permit applications for construction in rural and unused land areas, helped to unlock investment in rural areas across the state, while existing transmission infrastructure in renewable energy hotspots made new generation cheaper (McGreevy et al. 2020). Coal generation was phased out by the end of 2016 after providing a 35 percent share in 2010. Meanwhile, the share of renewable generation in 2021 reached over 65 percent of total generation, second in the world only to Denmark (Figure B2.1) (SAFA 2020; McGreevy and Baum 2021). Over the course of this transition, wholesale electricity prices in South Australia saw three brief spikes that exceeded those of other states in the national energy market, in 2007, 2010, and 2016, but otherwise prices have trended roughly in line with those in neighboring states (Australian Energy Regulator 2022). In recent years the average price of energy in South Australia (AU$44.83/MWh) has fallen below the price in two of the most populous states, Queensland ($61.81/MWh) and New South Wales ($64.81/MWh) (AEMO 2021b).

The region's favorable wind and solar resources could be rapidly developed due to a combination of early federal and state government targets. Following a federal mandate in 2009 to reach 20 percent of consumption with renewables by 2020, the South Australia state government introduced its own, more ambitious 2020 target of a 26 percent share, the only Australian state to do so. Upon realizing the target would be exceeded, South Australia again increased its

(continues)

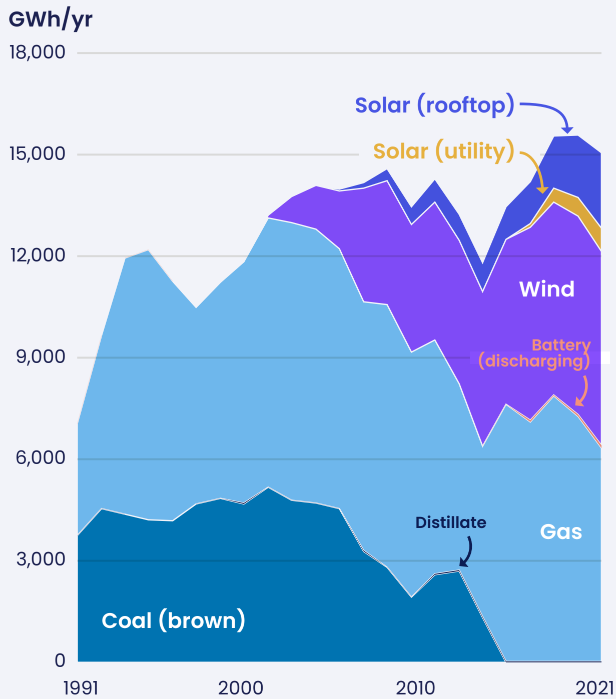
BOX 2 | A case-study of South Australia's renewable energy targets and sectoral transformation (continued)

FIGURE B2.1 | Annual electricity generation by region in 2019



Note: VRE = variable renewable energy.
Source: SAFA (2020).

FIGURE B2.2 | Electricity generation by source in South Australia



Note: GWh/yr = gigawatt-hour per year.
Source: OpenNEM (2022).

ambition level beyond national-level policy to achieve 100 percent renewables in 2030, with a view to reach 500 percent by 2050 by exporting the excess power (CER 2022; McGreevy and Baum 2021).

The early adoption of grid-scale batteries was important in accommodating the very high levels of renewable generation seen in recent years (Figure B2.2), with South Australia building the world's largest battery at the time in 2017, and three more since (CEFC 2021). In addition, the high number of rooftop solar systems in South Australia, now installed on over 40 percent of homes, is being accommodated by the uptake of household batteries, which were incentivized by state government subsidies (SAFA 2020). Most recently, the government has embarked on building the world's first green hydrogen plant to provide seasonal storage capacity. An innovative data-driven approach is also now being trialed to dispatch power stored in household batteries during peak times, which will help reduce burdens on the local grid.

Some key lessons can be taken from South Australia's experience. First, it exemplifies how cities, states, and other regional jurisdictions can go above and beyond federal ambitions and use their local powers and authorities to galvanize positive change. Second, it demonstrates that political facilitation—particularly the setting of highly ambitious targets—enables a critical mass of renewable capacity to be built, at which point it creates a level of momentum that is then difficult to derail (McGreevy and Baum 2021). Alongside these targets, investments in critical enabling technologies such as battery storage are crucial, including subsidies for households for batteries and distributed energy resources. Finally, streamlined planning regulation and ensuring adequate transmission infrastructure in renewable energy resource hotspots were similarly crucial to South Australia's renewable energy success story.

long durations (e.g., industry and shipping) (Hassan et al. 2021). Extensive research is needed to develop safe and cost-effective storage vessels to store and pipe hydrogen at scale (Abdalla et al. 2018), but here again scaling is constrained by energy density, capacity, and cost, challenges that will require greater investment in research and development to resolve (Koohi-Fayegh and Rosen 2020).

Improve market conditions and regulations to accelerate renewable uptake

In many regions, energy markets are tailored toward a system with a few large, centralized power suppliers. However, this landscape is changing quickly, with smaller, distributed (variable) generators coming online. Power supply, transmission, and distribution systems will need to be expanded and upgraded to integrate the new zero-carbon suppliers into the grid. Yet, in some cases, markets and regulations have not kept pace with these changes, and at times they have even blocked zero-carbon suppliers. For example, coal plants in Vietnam are guaranteed certain hours, meaning that zero-carbon supplies (hydro, solar, and wind) are curtailed during periods of excess generation (IEEFA 2020).

Currently, constructing the necessary infrastructure can take several years due to arduous permitting procedures (Tenggren et al. 2016). For example, recent evidence from the United Kingdom shows that construction-ready renewable projects are being delayed by almost 10 years due to bureaucratic and outdated planning protocols. Governments, planning divisions, and regulations can simplify permitting processes for renewables to speed up project implementation, allowing low-carbon suppliers to come online quickly (Ciupuliga and Cuppen 2013). Further, grid regulators and managers should evaluate existing market structures to identify any biases against small distributed suppliers (Komendantova and Battaglini 2016). Yet bureaucratic hurdles aren't all that can delay or obstruct projects. Local residents often oppose the construction of new energy infrastructure, such as wind turbines or transmission lines, presenting a significant barrier to implementation and one that can be difficult to overcome.

To accommodate high quantities of variable renewable energy supplies, it is widely accepted that power systems will need to become more flexible and add more storage (IPCC 2022b). Even if the potential for flexibility and storage is large, electricity markets need significant reform to unlock this potential (Energy Systems Catapult 2021). Consumers who own distributed renewable energy that provides backup capacity, demand flexibility, and storage need a fair, accessible, and convenient market setup to make participation attractive. Fortunately, we have all the technical know-how needed to establish such a system, but it will take significant practical changes: for example, smart tariffs could be rolled out to encourage customers to use electricity differently,

and market price enhancements would need to be implemented to better reward low-carbon or high-flexibility players.

Finally, negative environmental externalities from fossil fuels, such as local air pollution and water abstraction and discharges, can also be targeted. Since the environmental impact of zero-carbon power is negligible, these policies and regulations can promote clean energy build-outs. For example, national regulations on air quality (specifically emissions of nitrogen oxides) were a significant contributor to decreasing coal consumption in North America and the European Union (Duncan et al. 2016).

Tackle vested interests to achieve fossil fuel phaseout

Powerful vested interests are currently a significant barrier that is stymying progress in achieving a sustainable energy transition. Government budgets are often entangled with carbon dioxide emissions because a high proportion of their tax revenue is dependent on income from fossil fuels (e.g., royalties on oil and gas extraction) (OECD 2018). Also, the political and economic power of incumbent fossil fuel industries remains substantial (Piggot et al. 2020). There are close links between fossil fuel industry actors, political systems, regulations, and financial institutions, which generate vested interests that undermine the clean energy transition (Curran 2020; Bang and Lahn 2020; Strambo and González Espinosa 2020).

An estimated US$128 billion in direct subsidies was given to support fossil fuels in the power sector in 2017 out of total fossil fuel subsidies of $447 billion (Taylor 2020), meaning that renewables are competing against artificially cheaper fossil fuel alternatives (Schmidt et al. 2017). There is growing consensus that removing fossil fuel subsidies can be a highly effective tool for GHG mitigation (see Finance Indicator 6), while also yielding substantial co-benefits, such as reduced inequality and air pollution (Coady et al. 2017; Monasterolo and Raberto 2019; Li and Sun 2018). Removing fossil fuel subsidies would be made easier by redesigning governance structures to limit the influence of vested interests and overcoming public opposition to removal of fossil subsidies through clear communication, a phased process, and compensatory policies targeted to assist the poorest people who may no longer be able to afford energy.

Create social and economic protections to sustain just and equitable transitions to a net-zero future

The transition to a zero-carbon power system will involve considerable disruption to local communities as existing fossil plants are shut down and coal and gas production declines, not only displacing the workers in these fields but also impacting people and employment in downstream value chains, as well as national and subnational government revenues. Although the energy transition could create as many as 30 million net new jobs globally, these gains will be unevenly distributed and will often not arise where job losses occur, particularly in coal mining communities (Cozzi and Motherway 2021). Moreover, the quality and longevity of jobs in the global sustainable energy sector is not well understood. There is also currently a critical lack of qualified workers to fill these newly created roles (IEA 2021h). If handled in the wrong way, this transition will be unjust and create political, social, and economic barriers to decarbonization, as the resultant job losses and geographical displacement will decrease public support for its achievement.

Managing this transition will require support to increase labor mobility and socioeconomic protections. As fossil operations are taken offline, measures to ensure that worker dislocation is minimized, such as retraining programs and economic diversification strategies, could be implemented (Mayer 2018; Pollin and Callaci 2019). Those who are displaced could be supported with schemes such as relocation measures and cash transfers in parallel with fossil phaseout strategies. Meanwhile, plans to ensure supplies of qualified workers to support the transition, including worker retraining, upskilling, and knowledge transfer, as well as advancing educational and apprenticeship programs for young people, will be important (Lucas et al. 2018). Also, social safety nets, early retirement schemes, universal basic income grants, or creation of active labor markets could support workers unable to transition to a new sector.

The transition also offers an opportunity to create more equitable societies and diverse workforces, if carefully planned and implemented (Pearl-Martinez and Stephens 2016). For example, evidence from South America shows higher engagement of women and ethnic minorities in the emerging clean energy sector compared to fossil fuels (Ravillard et al. 2021). Meanwhile, clean energy projects are helping communities lift themselves out of poverty in even the most isolated regions. For instance, despite dire poverty and conflict conditions, residents in Gaza, Palestine, have deployed community finance schemes to rapidly scale microsolar infrastructure (+500 percent since 2015), decreasing their dependence on expensive and polluting diesel fuels (Fischhendler et al. 2022). In addition to the economic gains, there will also be health benefits from the transition to clean energy given that the localized negative impacts of fossil-based electricity generation have been shown to disproportionately affect people of color and those with lower incomes in both developed and developing countries (Carley and Konisky 2020). Yet realizing a transition that capitalizes on opportunities and minimizes negative impacts on societies requires regional leadership and planning. Governments can begin by identifying local risks and opportunities from the transition and set out frameworks as a guide to implementation, as recently done by South Africa's Presidential Climate Commission (PCC 2022).

The fossil fuel industry causes undue impacts on human and environmental health—for example, through oil spills and air and water pollution. We must not make the same mistakes in the clean energy transition. Human injustices are already prevalent in existing supply chains of zero-carbon technologies, a matter that needs to be urgently addressed to stop problems from escalating as demand for minerals such as cobalt increases. Many of the world's largest clean energy technology companies have strong links to mines with appalling working conditions, with some operators facing allegations of corruption, land and human rights infringements, violence, and deaths from dangerous work conditions (BHHRC 2020). Moreover, these mines are located in some of the world's poorest areas and often overlap with protected key biodiversity areas, causing damage to local ecosystems (Sonter et al. 2020). Companies could adopt and implement strong human rights policies and corporate procurement, in line with the UN Guiding Principles on Business and Human Rights, and set up due diligence departments to ensure that policies are being followed (BHHRC 2020). Yet it is also important to acknowledge that negative social impacts are not unique to zero-carbon technologies.

Promote demand-side flexibility and management

Effective mitigation policies target electricity demand as well as supply. Decarbonization of sectors such as transport and industry will require a high degree of electrification, implying large future increases in electricity demand (e.g., Lechtenböhmer et al. 2016; Zhang and Fujimori 2020). This barrier can be addressed by reducing existing demand through efficiency measures and innovatively shifting and switching off demand (a process known as demand-side management).

Meeting future energy demands efficiently is essential for zero-carbon power transitions as it circumvents the need for additional costly infrastructure (Bertoldi and

Mosconi 2020). Energy efficiency measures, such as appliance efficiency standards, and mandatory energy performance standards in buildings, have seen success in the European Union, for example (Malinauskaite et al. 2019; Economidou et al. 2020; Sun et al. 2021). Yet vast untapped opportunities remain to improve energy efficiency, and policy programs could target areas such as repairing aging electricity assets (Surana and Jordaan 2019), heat pumps and district heating and cooling networks (Gaur et al. 2021; Zhang et al. 2021), and retrofitting or insulating existing buildings (Alam et al. 2019).

In addition to using energy more efficiently, we also need to better control demand in real time, primarily by shifting, increasing, or reducing demand instantaneously without compromising performance, to match available supplies of intermittent renewable energies. Demand flexibility programs are already showing great promise. For example, in the United Kingdom, industrial consumers of electricity, such as manufacturing plants, are widely participating in national demand-response programs, which is increasing renewable energy uptake and saving consumers large sums in electricity bills. Rolling out flexibility programs to the domestic sector with solutions such as vehicle-to-grid and active demand management with smart meters could save UK energy utilities and grid operators up to £60 billion to 2050 (Qadrdan et al. 2017). Establishing such demand-side management schemes requires an accommodative regulatory framework that encourages the establishment of companies that act as demand aggregators and that can coordinate instantaneous and large-scale demand reductions.

SECTION 3

Buildings

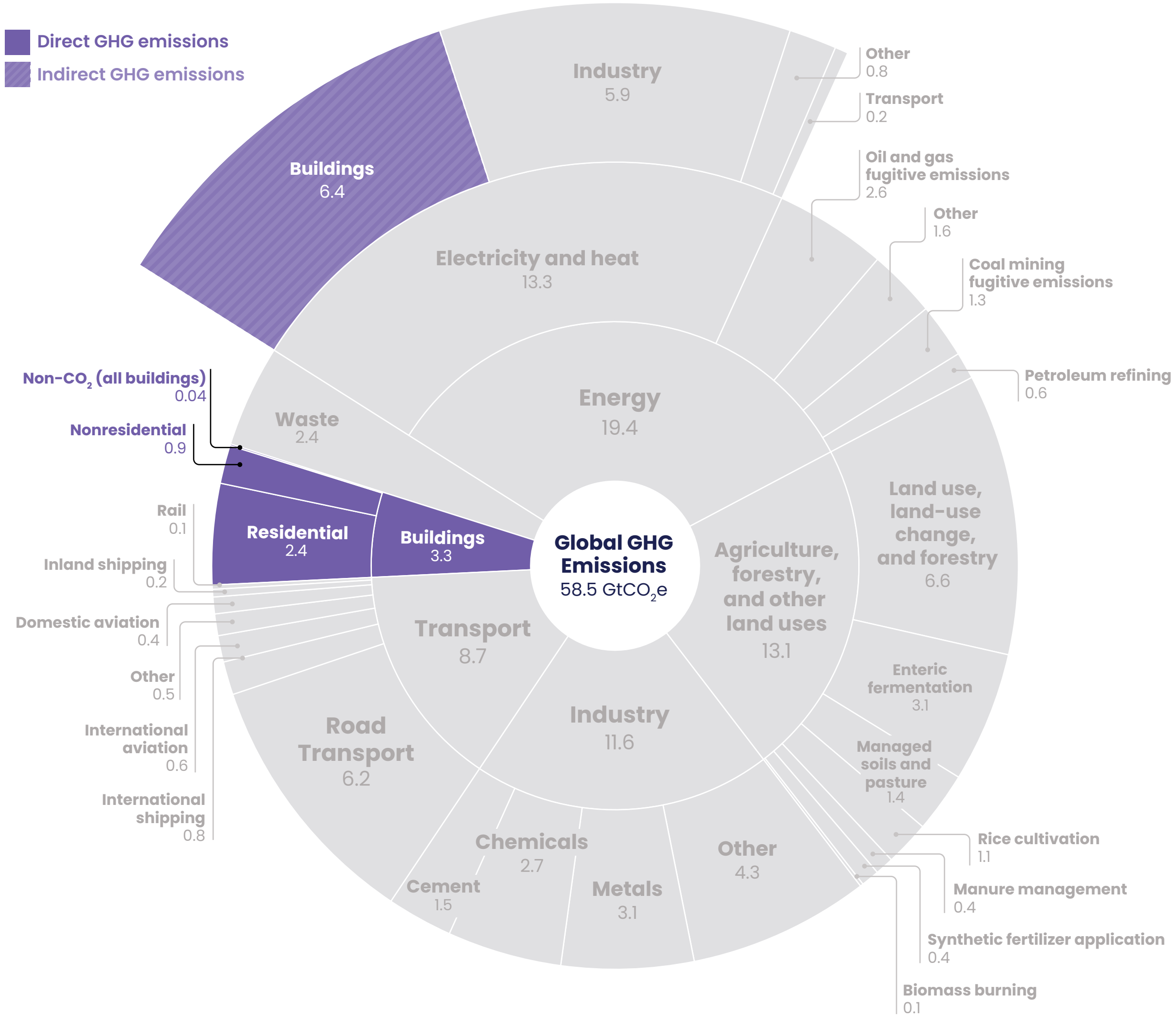
Burning fuel for cooking and heating directly emits 5 percent of GHGs globally. When accounting for GHGs released from electricity use and heat consumption for heating, cooling, cooking, lighting, and electronics, this figure triples to 17 percent of the world's GHG emissions (Figure 13). Constructing and furnishing buildings generates additional greenhouse gas emissions, raising the share to 21 percent (Box 3) (IPCC 2022b). Emissions from buildings have increased steadily since 1990, driven predominantly by electricity consumption (Figure 14) (IEA 2020h). Changing behaviors during the COVID-19 pandemic—namely, teleworking and the decline in hotel occupancy and restaurant dining—led to a drop of about 10 percent in carbon dioxide (CO_2) emissions from buildings in 2020 compared with the year before (IEA 2021j; UNEP 2021a). However, preliminary data for 2021 indicate that global GHG emissions from building operations have already rebounded to prepandemic levels (IEA 2022c).

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. Furthermore, larger buildings also produce higher embodied emissions through the greater volume of construction materials used. The amount of floor area and energy used per capita differs vastly across countries and within countries, often depending on the country's level of wealth.

Reducing the energy intensity of buildings (the amount of energy used per square meter [m^2] of floor area, including heating, cooling, and appliances) further helps to minimize overall energy demand from the sector. Energy-efficient technologies are key to reducing overall demand, while improvements to building design, including orientation, air flow, facades, and color, reduce the need for active heating or cooling. A final key component to eliminating emissions from buildings operations is to reduce the emissions intensity of remaining energy use. Energy use can be decarbonized by switching the energy source for heating and cooking equipment from fossil fuels to electric power, and decarbonizing the power supply (Power Indicators 1–4).

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 embodied emissions (Box 3). Decarbonizing existing buildings will require a high annual rate of deep retrofits that drastically improve energy efficiency and replace equipment with zero-carbon options (Table 3).

FIGURE 13 | Buildings' contribution to global GHG emissions in 2019



Notes: CO_2 = carbon dioxide; GHG = greenhouse gas; $GtCO_2e$ = gigatonnes of carbon dioxide equivalent.
Source: Minx et al. (2022), described in Minx et al. (2021) and used in IPCC (2022b).

TABLE 3 | Summary of global progress toward buildings targets

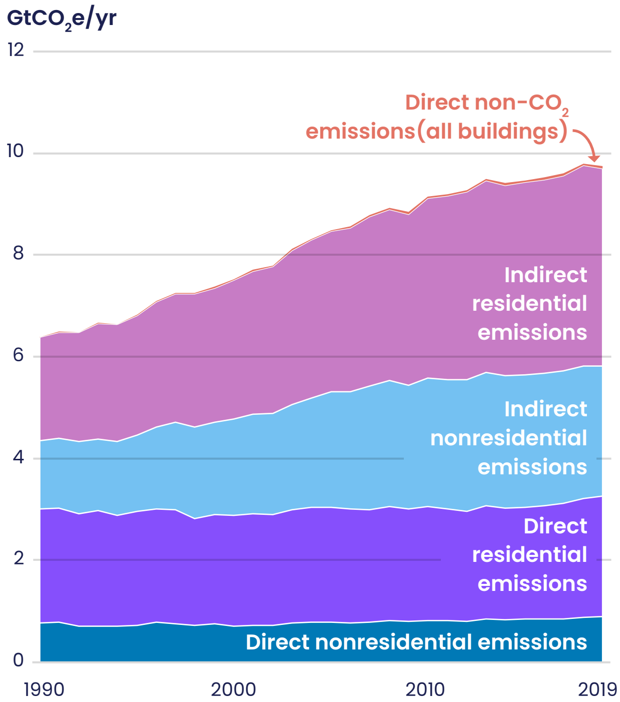
INDICATOR	MOST RECENT DATA POINT (YEAR)	2030 TARGET	2050 TARGET	TRAJECTORY OF CHANGE	ACCELERATION FACTOR	STATUS
Energy intensity of building operations (% of 2015 levels)[a]	98 (2019)	70–80 (residential) 70–90 (commercial)	40–80 (residential) 50–85 (commercial)		7x (residential) 5x (commercial)	×
Carbon intensity of building operations ($kgCO_2/m^2$)	30 (residential) (2017) 61 (commercial) (2017)	10–16 (residential) 15–21 (commercial)	0		Insufficient data	?
Retrofitting rate of buildings (%/yr)	<1 (2019)	2.5–3.5	3.5 (2040)		Insufficient data	?

Note: %/yr = percent per year; $kgCO_2/m^2$ = kilograms of carbon dioxide per square meter.

[a] Energy intensity is the amount of energy used per square meter of floor area, including heating, cooling, and appliances. Publicly available data report only energy intensity trends for all buildings combined, not for residential and commercial buildings separately. In calculating acceleration factors, we use this combined energy intensity trend and assume that the historical rate of change is the same for both types of buildings.

Sources: Historical data from IEA (2020c, 2019a, 2020b, 2020i, 2020c, 2020g, 2021i); targets from Climate Action Tracker (2020a).

FIGURE 14 | Global GHG emissions from buildings



Notes: CO_2 = carbon dioxide; GHG = greenhouse gas; $GtCO_2e/yr$ = gigatonnes of carbon dioxide equivalent per year.

Source: Minx et al. (2022), described in Minx et al. (2021) and used in IPCC (2022b).

BOX 3 | Emissions from constructing and furnishing buildings

The GHG emissions addressed in this section are known as a building's "operational" emissions—those that occur over the building's lifetime from activities happening within it. Producing and transporting materials to construct and furnish buildings also generates GHG emissions, known as "embodied" emissions. Embodied emissions are not covered in this section, but in Section 4 we examine how the emissions intensity of two key construction materials—cement and steel—can be reduced.

The Human Settlements Pathway developed by the Marrakech Partnership sets out targets for reducing embodied emissions over the next three decades. Embodied carbon must be reduced by at least 40 percent by 2030, with leading projects achieving at least 50 percent reductions in embodied carbon. By 2050, at the latest, all new and existing assets must be net zero across the whole life cycle, including operational and embodied emissions (Marrakech Partnership and Global Climate Action 2021).

Taking a whole-life-cycle perspective when constructing a building means accounting for both embodied and operational emissions, and what happens to the building and furnishings at the end of its current use. Using low-carbon construction materials, designing buildings to use materials efficiently, and planning for the reuse or recycling of material at the end of the building's lifetime can all contribute to lowering its overall emissions. Refurbishing and restoring old buildings, instead of demolishing and rebuilding them, is also important in minimizing construction-related emissions.

Status of buildings indicators

BUILDINGS INDICATOR 1:

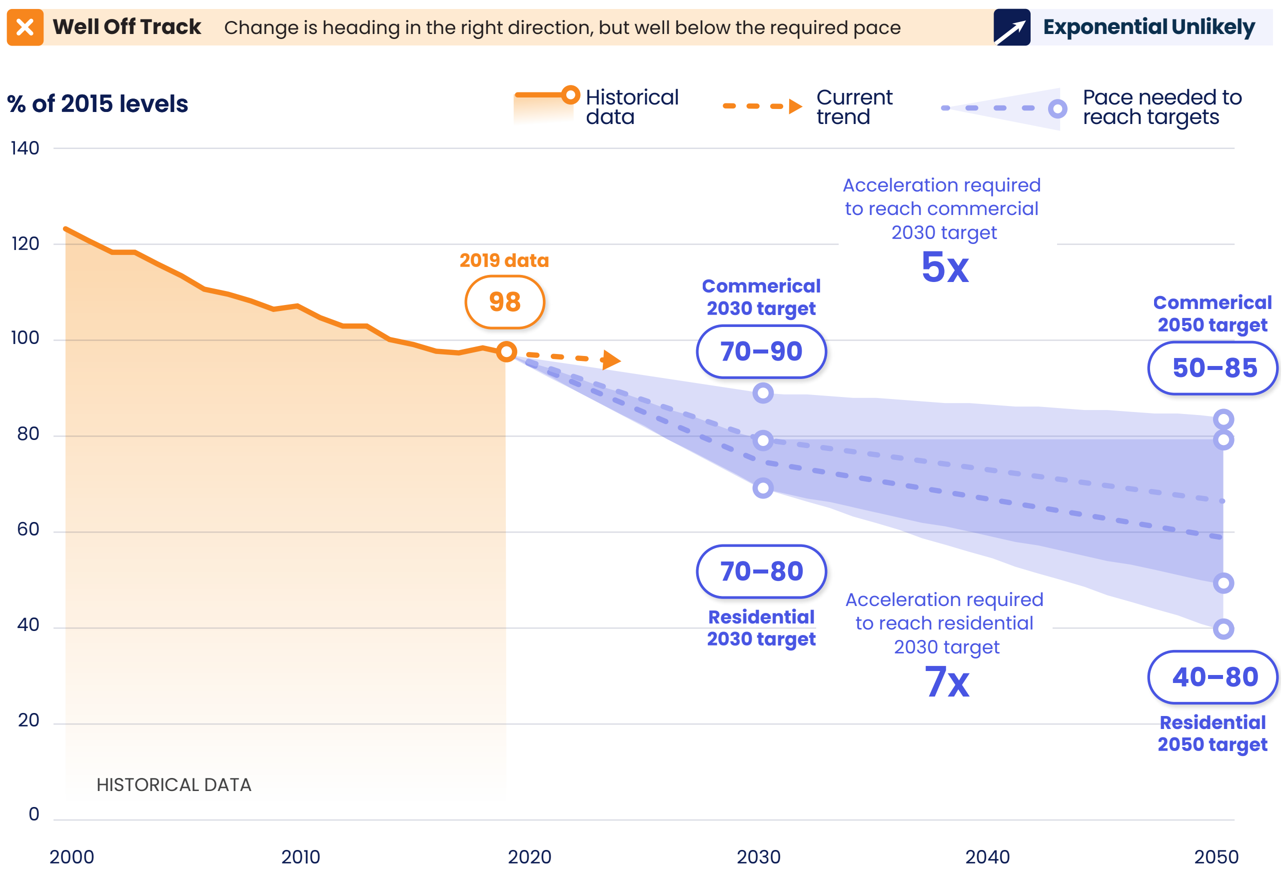
Energy intensity of building operations (% of 2015 levels)

- **Target**: The energy intensity of residential building operations in key countries and regions drops by 20–30 percent by 2030 and by 20–60 percent by 2050, relative to 2015. For commercial building operations, energy intensity in key countries and regions falls by 10–30 percent by 2030 and by 15–50 percent by 2050, relative to 2015.

Energy intensity is the amount of energy used per square meter of floor area, including heating, cooling, and appliances. The energy intensity of building operations declined during the 2000s and 2010s, but progress has slowed in recent years (Figure 15). Globally, the energy intensity of building operations decreased by 20 percent from 2000 to 2015 and only another 2 percent from 2015 to 2019 (IEA 2020a). The slowdown in progress is being driven by an increased demand for electricity for cooling and use of digital devices (IEA 2020h).

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 improving more quickly, while most other regions, including China, have seen only a smaller improvement in energy intensity (IEA 2020a). To achieve 2030 targets, gains made from 2015 to 2019 would need to accelerate by a factor of five for commercial buildings and seven for residential buildings.

FIGURE 15 | Historical progress toward 2030 and 2050 targets for energy intensity of residential and commercial building operations



Note: Energy intensity is the amount of energy used per square meter of floor area, including heating, cooling, and appliances. Publicly available data report only energy intensity trends for all buildings combined, not for residential and commercial buildings separately. In calculating acceleration factors, we use this combined energy intensity trend and assume that the historical rate of change is the same for both types of buildings. Acceleration factors for residential and commercial buildings are calculated for the midpoint of the corresponding target range.

Sources: Historical data from IEA (2020c, 2019a); targets from Climate Action Tracker (2020a).

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

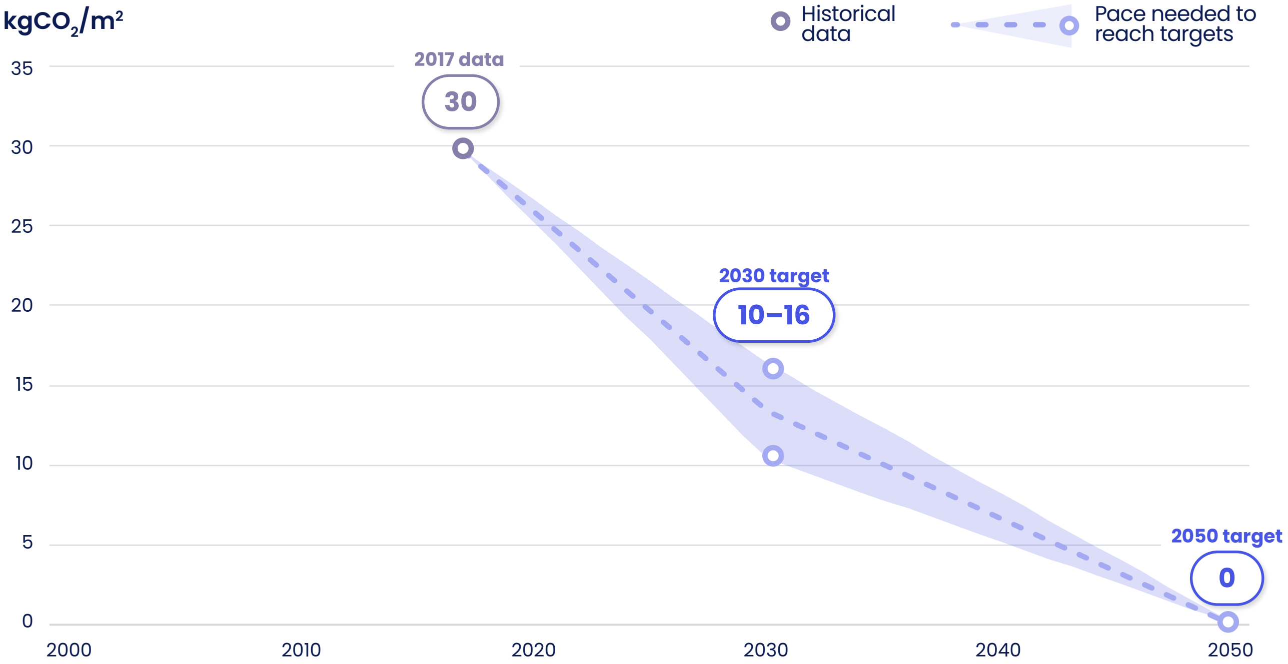
- **Target**: In select regions, the carbon intensity of residential building operations is 45–65 percent lower by 2030 than in 2015 and the carbon intensity of commercial building operations is 65–75 percent lower.[15] By 2050, all buildings in the world reach close to zero-carbon intensity.

Carbon intensities of buildings are calculated by dividing total CO_2 emitted by global total floor area. For all buildings (residential and commercial floor area combined), the average global carbon intensity has steadily decreased since 2000. The pace of reduction was insufficient to counteract 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 continued to rise (IEA 2019b, 2020b).

Carbon intensity reductions were greater in commercial buildings than residential buildings, but the carbon intensity of commercial buildings still remains at least double the carbon intensity of residential buildings (IEA 2019b). Reducing carbon intensities requires that the equipment be electric and that the power grid be decarbonized or that on-site renewables be installed. Data limitations prevent a full quantitative assessment of progress made toward reducing the global average carbon intensity of residential and commercial buildings (Figures 16 and 17)—only a single year of disaggregated data is publicly available for commercial and residential floor area. These data limitations mean that it is not possible to calculate how much recent changes must accelerate to be on track to meet the 2030 target. However, the evidence suggests that the emissions intensity indicators are not on track globally. The carbon intensity of building operations may experience some form of nonlinear, rapid decrease in the coming decades, particularly as more buildings implement decarbonization measures due to market and policy demands, but achieving such dramatic reductions will require appropriate support by a wide range of decision-makers.

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

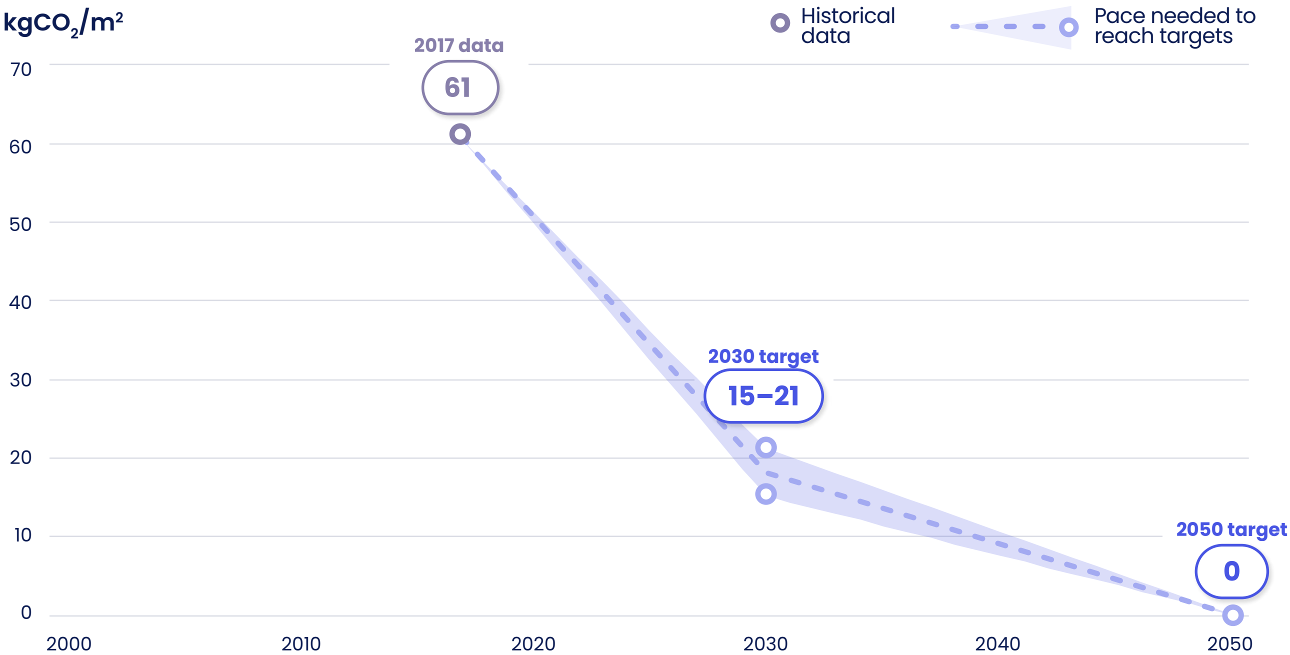
Insufficient Data Data are insufficient to assess the gap in action required for 2030 **Exponential Possible**



Note: $kgCO_2/m^2$ = kilograms of carbon dioxide per square meter.
Sources: Historical data from IEA (2020b, 2020i, 2019a, 2020c); targets from Climate Action Tracker (2020a).

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

Insufficient Data Data are insufficient to assess the gap in action required for 2030 **Exponential Possible**



Note: $kgCO_2/m^2$ = kilograms of carbon dioxide per square meter.
Sources: Historical data from IEA (2020b, 2020i, 2019a, 2020c); targets from Climate Action Tracker (2020a).

BUILDINGS INDICATOR 3:

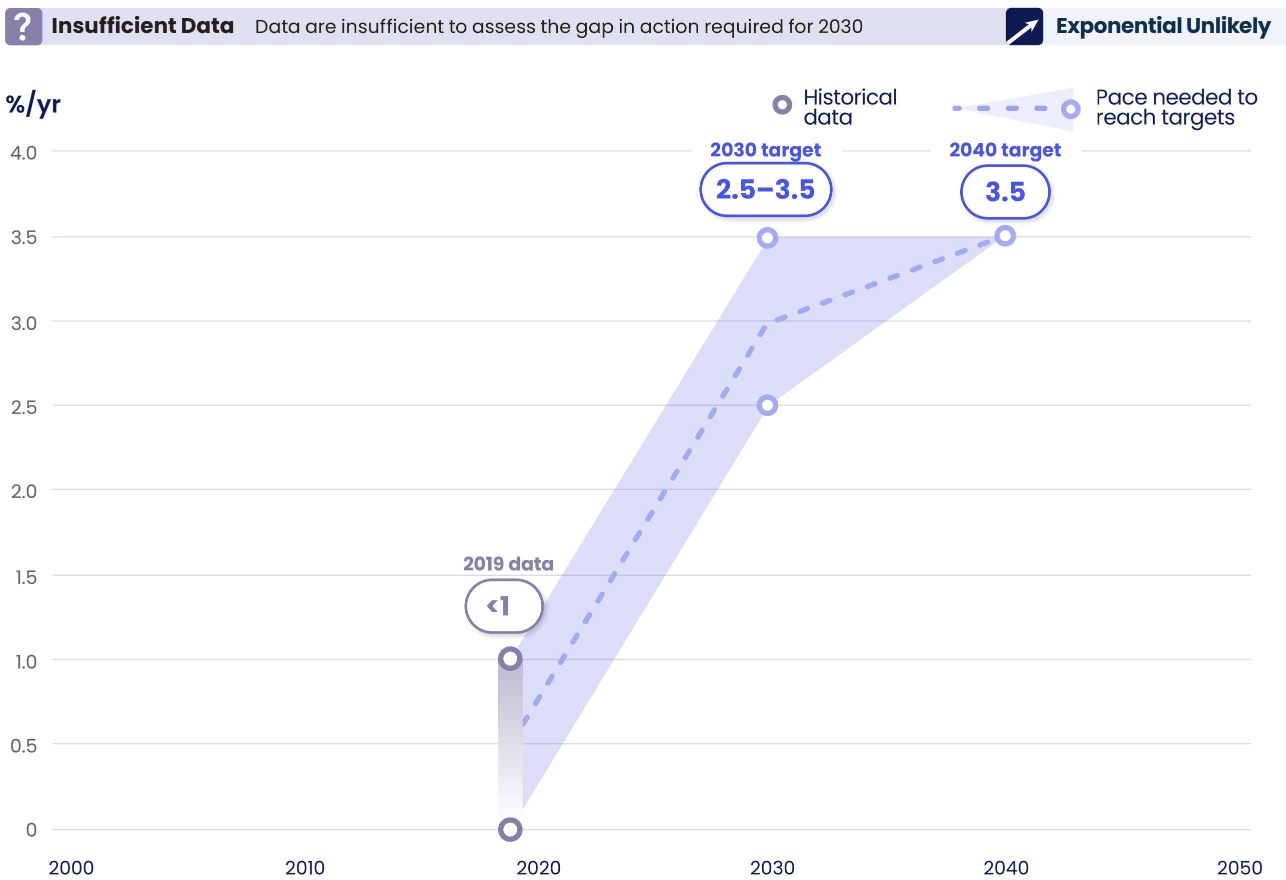
Retrofitting rate of buildings (%/yr)

- **Target:** 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.

Buildings need to be retrofitted to improve their energy efficiency, minimizing heat gain and loss and reducing the need for active measures of heating or cooling. Heating and cooking equipment needs to be electrified, and, in some cases, on-site renewable energy needs to be installed. The retrofitting rates of this indicator refer to deep retrofitting, which goes significantly beyond current conventional practice by maximizing energy efficiency improvements and incorporating zero-carbon technologies.

Data on deep retrofitting rates do not exist for many countries; where data are available, the information is usually for single years (e.g., European Commission 2022a). However, according to the International Energy Agency (IEA), less than 1 percent of buildings are retrofitted every year (European Commission 2022a; IEA 2020g, 2021i) (Figure 18), which is well below the 2.5–3.5 percent a year required to meet the targets. It is not possible to give a quantitative estimate of how much recent change needs to accelerate to meet the 2030 target, but it is clear that the pace of retrofitting needs to increase drastically in the coming decade.

FIGURE 18 | Historical progress toward 2030 and 2050 targets for retrofitting rate of buildings



Sources: Historical data from IEA (2020g, 2021i); targets from Climate Action Tracker (2020a).

Global assessment of progress for buildings

Substantial improvements across buildings are needed to meet the Paris Agreement's goal of limiting the rise in global temperature to 1.5°C. GHG emissions from buildings operations are continuing to grow, driven primarily by rising emissions from electricity use (Figure 14). The data that are publicly available indicate that none of the indicators assessed is on track. Space and water heating dominate global energy demand from buildings, together accounting for more than 50 percent of global energy demand from buildings in 2019 (UNEP 2021a; IPCC 2022b). However, energy demand has grown more quickly for other end uses in buildings since 1990, especially connected and small appliances (280 percent), cooking (89 percent), and cooling (75 percent) (IPCC 2022b).

Total floor area is expected to continue to grow in the coming decades, and may reach up to double 2020 levels by 2060 in response to rising demand (UNEP and IEA 2017). Much of this growth is anticipated to occur in Asia and Africa, and steps can be taken now to ensure that improved standards of living can go hand in hand with minimizing CO_2 emissions from construction and additional demand for thermal comfort (UNEP 2021a). Although the fundamental steps of improving energy efficiency to reduce overall energy demand and decarbonizing energy supply apply broadly, the building sector is highly diverse and specific actions for individual buildings vary greatly. Different climatic zones require different approaches to meet heating and cooling needs, for example. Other features that determine the appropriate mitigation strategy include the type of building (residential or commercial), whether it already exists or is yet to be built, what infrastructure (such as gas connections) already exists, and the type of fuels used to power it. The structure of energy demand in buildings in sub-Saharan Africa differs substantially from other regions; many people today rely on traditional biomass for cooking and heating, implying a suppressed demand for electricity.

But across contexts, the zero-carbon and energy-efficient technologies needed already exist and are fairly mature (IEA 2019b; Urge-Vorsatz et al. 2020). Energy efficiency measures for building structures need to be tailored to the building and its location. These measures include insulating lofts, installing double- or triple-glazed windows, reducing thermal bridges, orienting new buildings to optimize shade and thermal heat gain, installing shutters and blinds, putting in cool or green roofs, and ventilating properly (to maintain occupant health, regulate air flow and humidity, and prevent mold growth). Digital sensors and controls can optimize energy use (IEA 2019b).

Heat pumps[16] are a key technology for space and water heating, and for space cooling; rapidly scaling up their use is a major component of all building decarbonization scenarios because they are highly efficient and allow heating to be provided by clean electricity (IEA 2019b, 2021m; ETC 2018b). Recent improvements in technology mean that they can now work in very cold climates and be used for cooling in regions where both heating and cooling are required. Heat pumps distribute water at lower temperatures than gas or oil boilers, however, and therefore rely on thermally efficient buildings to be most effective, adding to the need for energy efficiency measures. Heat pumps also use refrigerants, many of which can contribute significantly to global warming. Under the Kigali Amendment to the Montreal Protocol, over 100 countries have already committed to phase down the use of refrigerants with a high global warming potential. Viable alternatives to these refrigerants with low global warming potential do exist; it is critical that as heat pumps and air conditioners are widely installed, they use these alternative refrigerants (IEA 2021l).

Increasing heat pump sales can be an early sign of progress; in some regions, sales have already increased rapidly, reaching 11 percent of market share for heating technologies in 2020 (Box 4) (IEA 2021m). Increasing the use of heat pumps will increase electricity demand, so eliminating emissions from buildings also requires careful management and decarbonization of the power supply (see Section 2).

Other technologies that can help regulate temperature in buildings include district heating[17] or cooling and solar thermal water heating. Integrating district heating and cooling in a decarbonization strategy relies on zero-carbon thermal energy sources. Biomass is commonly used

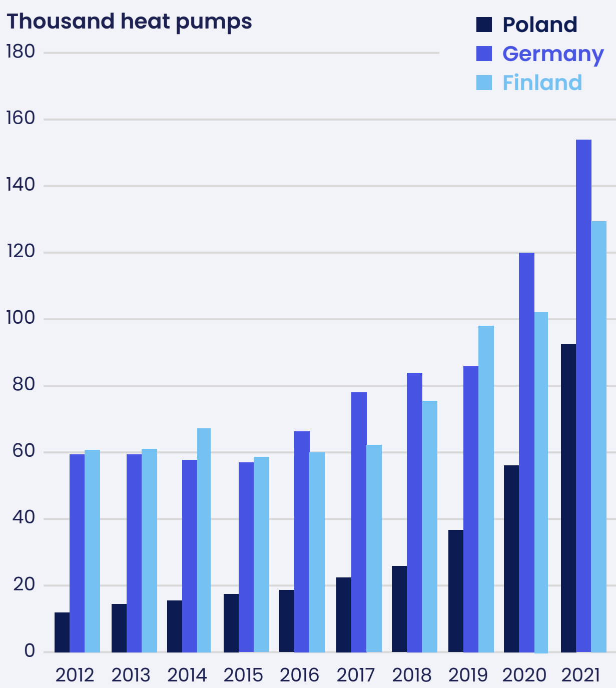
BOX 4 | Accelerating heat pump sales are an encouraging sign of progress

The number of heat pumps installed increased in recent years, particularly in new buildings in Europe, North America, and Asia. Financial incentives to cover a part of the up-front costs, as well as labeling and efficiency standards, have supported adoption of this technology in recent years (IEA 2020k).

Heat pumps are already playing an important role in decarbonizing buildings, especially in regions with moderate climates that require both heating and cooling. Sales of heat pumps are increasing globally and across all regions with high heating demand (IEA 2020k). After a slight slowdown in 2020, heat pump sales rebounded in 2021 in many countries. In Poland, for example, a combination of regulatory and incentive policies combined with changed perceptions supported the rapid uptake of heat pumps (Rosenow and Gibb 2022; Morawiecka and Rosenow 2022). In 2020 and 2021, the number of heat pumps sold for space heating increased by 80 percent each year, reaching almost 14 percent of heat generator sales in 2021 (SPIUG 2022; PORT PC 2022) (Figure B4.1). Sustained demand in countries such as Norway and Sweden shows that heat pumps can become the dominant technology (Rosenow and Gibb 2022).

However, global sales need to increase substantially if heat pumps are to become the dominant technology in new buildings and to replace fossil fuel–powered boilers in existing ones. Under the International Energy Agency's Net Zero by 2050 scenario, the number of heat pumps installed needs to increase by a factor of 10 between 2020 and 2050 (IEA 2021h). Achieving this increase will require new regulations, changes to financial incentive structures, and knowledge-building for homeowners and occupiers.

FIGURE B4.1 | Annual heat pump sales in northern Europe



Note: Data here include heat pump sales for both space and water heating.
Sources: Rosenow and Gibb (2022); PORT PC (2022).

as a renewable source, but it is a Paris Agreement–compatible option only if its sustainability is assured and its life-cycle emissions are near zero.

Although the technologies are similar, the process and challenges for reaching zero-carbon buildings differ for new and existing buildings. Where most of the building stock that will exist in 2050 has already been built—as is the case in Europe, the United States, Canada, Australia, and increasingly China—retrofitting is more important (Liu et al. 2020; IEA 2019b). For new construction, building to zero-carbon specifications is much less expensive than retrofitting over the next two to three decades (Currie & Brown and AECOM 2019).

Heated or cooled floor area per capita is still low in developing countries. But urbanization and rapid population and economic growth will increase demand for new floor space (UNDESA 2019). This rapid growth will require particular attention to the design and construction of new buildings, including material efficiency to limit embodied carbon (Adams et al. 2020).

Furthermore, in a world where climate change causes higher average temperatures, with impacts on health and ability to work, cooling needs will become especially important. Sales of air conditioners grew rapidly in recent years. The fastest growth was in India, where sales rose by about 15 percent a year between 2010 and 2019, although air conditioner ownership still remained below 10 percent in 2019. (IEA 2020j, 2021k). Installing highly efficient air conditioning equipment is essential to limit the growth in energy demand caused by the increase in active cooling (IEA 2021k). The energy needed to cool spaces can be reduced or eliminated through passive cooling measures, including insulation, reflective surfaces, shading, green infrastructure, and natural ventilation (UNEP 2021f). It's important that these elements be incorporated into the design and construction of new buildings to minimize the need for active cooling, and the consequent demands for zero-carbon electricity.

Mitigating climate change is not the only benefit of reducing the energy and carbon intensity of operation of buildings. Doing so also yields health benefits through improved indoor air quality; more comfortable living and working spaces; lower energy poverty; and increased energy resilience, energy security, and price stability (Ortiz et al. 2019; Urge-Vorsatz et al. 2020; von Stechow et al. 2015).

Energy expenditures can be a significant portion of household spending, and increased energy prices disproportionately affect low-income households (Steckel et al. 2022; Nicholls et al. 2017). If not managed properly, the higher up-front cost of many decarbonization measures in buildings can lead to higher rents or increased overall building costs. In addition, where new buildings are more expensive following the implementation of decarbonization measures, they become less affordable to first-time and low-income buyers. Conversely, implementing energy-savings measures can protect lower-income households from fluctuating energy prices. Appropriate financial instruments can be used to reduce up-front costs and ensure that occupiers benefit from energy savings.

Enabling conditions for climate action across buildings

Implementing mitigation measures for buildings faces a multitude of challenges. These include a lack of incentives for adopting energy efficiency measures, high up-front costs and financial risks, the complexity of the decision-making processes, competing priorities for key actors (e.g., landlords and tenants), and a lack of skills and training for the workforce. Many of these challenges can apply to the same building, and no single solution can address all challenges. Conversely, some solutions address multiple challenges. Experts recommend that a range of policies and strategies be implemented at the national and regional levels, adapted to the local organizational context.

Because space cooling and space and water heating dominate global emissions, the enabling factors described here focus on these activities. Specific recommendations for cooking, lighting, and appliances are not provided, but standards and regulations have proved effective in improving efficiency and could be further utilized (IEA/4E TCP 2021).

Manage competing priorities through regulation

Multiple actors—from property developers and banks to architects and engineers to tenants—are involved in the design, construction, and retrofitting of buildings. Each actor has its own priorities, knowledge, and decision-making capacities. They do not face sufficient incentives to prioritize energy efficiency and zero-carbon technologies in their decisions (Race to Zero et al. 2022). Initiating transformative change in the buildings sector will require coordinated action across this multitude of built environment actors (Race to Zero et al. 2022).

Regulation of energy demand and the carbon intensity of energy use in buildings can help manage the competing priorities of the various actors involved and is the most important policy instrument to decarbonize buildings (IEA 2021j; Economidou et al. 2020). Regulations can mandate the implementation of energy-saving measures and zero-carbon technologies. If well designed, regulations can also provide guidance on what actions are necessary or appropriate, provide clear signals to all actors, and align all actors behind a common goal.

Slightly different regulations are needed for new buildings as compared to existing ones, and for decarbonization of energy supply as opposed to reducing energy demand. By looking at regulations already in place, we can identify some of the factors for success in each of these cases.

Building energy codes are the most common regulatory instrument used. The number of countries with such codes rose from 62 in 2015 to 81 in 2020 (UNEP 2021a). Clear, well-communicated time frames for increasing the stringency of regulations have been shown to increase compliance. In the Netherlands and the city of Brussels, they even helped achieve targets early (Sunderland and Jahn 2021; Urge-Vorsatz et al. 2020; Cappelletti et al. 2016).

There is still significant potential for building regulations to improve energy and carbon intensities in most countries. This potential could be tapped by making existing regulations more stringent; expanding the coverage of regulations to more countries, including existing buildings as well as new buildings; and mandating fossil-free energy sources and reductions in energy demand (IEA 2019b; Hinge and Brocklehurst 2021; Climate Action Tracker 2022a).

Most energy components of building codes cover only new buildings; building codes that do cover existing buildings have not been able to ensure that retrofitting occurs at a high enough rate. One way to increase retrofitting rates is to apply minimum energy performance standards at trigger points, such as change of ownership, replacement of equipment, or specific years (Hinge and Brocklehurst 2021). The cities of Boulder and New York in the United States and Tokyo in Japan, as well as the countries of France, the Netherlands, and the United Kingdom, among others, have already adopted this approach. Initial compliance in Tokyo and Boulder was high; in the United Kingdom, it was limited; policies in other jurisdictions are not yet mature enough to assess. Factors for success appear to include adopting comprehensive policies, providing additional supportive measures, avoiding too many exemptions, ensuring compliance, and engaging stakeholders (Nadel and Hinge 2020; BPIE and CLIMACT 2021). As part of the European Union's "renovation wave," the European Commission recommends that EU member states adopt energy performance standards to ensure that the worst-performing buildings are upgraded by the end of this decade (European Commission 2021a, 2021b). In the United States, members of the recently launched National Building Performance Standards Coalition aim to adopt new legislation for building standards and stimulate retrofits in an equitable manner (National BPS Coalition 2022).

Energy improvements are only one part of mitigating emissions from buildings; decarbonizing the energy supply is equally important. Toward that end, many jurisdictions recently put in place regulations to phase out fossil fuels for heating in new buildings. These jurisdictions include Austria, France, Ireland, the Netherlands, the United Kingdom, and cities in the U.S. states of California, Missouri, Massachusetts, New York, and Washington (Climate Action Tracker 2022a; Gruenwald and Lee 2020; *Cooling Post* 2022). Some of these regulations ban new gas connections for new buildings; others utilize standards on energy intensity or require that new equipment not rely on direct consumption of fossil fuels.

Implementing regulations not only mitigates climate change; it can also increase energy security. In reaction to the 2022 Russian invasion of Ukraine, for example, most European countries are seeking to end imports of fossil fuels from Russia. These strategies include varying degrees of decreasing fossil fuel use altogether, including in the buildings sector. The Danish, Dutch, German, and UK governments have all announced plans to accelerate a switch away from gas heating in homes through new regulations.

Scale up financing models that minimize risk and improve affordability

The IEA estimates that cumulative additional investments of $14 trillion will be needed between 2018 and 2050 but that additional investment will lead to substantial long-term savings for consumers (IEA 2019b). Up-front costs can represent a barrier, and payback periods are often long and uncertain, increasing the perceived risks and decreasing the attractiveness of investment, even for options that are cheaper overall. Reducing overall costs and the financial risks around investing in zero-carbon buildings could increase their uptake and enhance compliance with regulations (Urge-Vorsatz et al. 2020; Dadzie et al. 2018; Du et al. 2014).

Investment in building energy efficiency is growing, rising 40 percent between 2015 and 2018, from $129 billion to $180 billion. Most of the increase came from a few European countries, however. These investments need to increase globally to meet the energy intensity targets (UNEP 2021a).

The most appropriate fiscal or financial instrument to boost public and private investments depends on the stage of market development, whether a building already exists or will be built, and existing policies. Multiple instruments may be needed (Bertoldi et al. 2021).

Direct financial support from governments in the form of grants and tax rebates can kick-start uptake of new zero-carbon technologies in buildings by lowering overall costs to the consumer (Bertoldi et al. 2021; IEA 2021l). In 2022, for example, the United Kingdom launched a new boiler upgrade scheme that provides £5,000 in grants to buildings that install low-carbon heating systems, including heat pumps (UK Government 2022). This kind of direct funding has limitations, however, as it depends on limited national budgets and instruments to fund the schemes and leverage private finance.

In addition, fiscal instruments, such as removing fossil fuel subsidies or changing tax structures, can be used to incentivize a shift to zero-carbon technologies (IEA 2021l). In many countries, the price of electricity can be two to three times that of gas, making electric technologies uncompetitive. When using fiscal instruments, policymakers must protect people at risk of energy poverty from increasing prices. Options to do so include redistributing tax revenues and ensuring energy upgrades of social and low-income housing to reduce costs.

Financial risks to the consumer of zero-carbon upgrades for buildings can be reduced through innovative finance models, such as energy performance contracts that reduce up-front costs and guarantee savings in the long term. In contract financing models, energy service companies take on the up-front payment and administrative burden and guarantee a particular energy service; the investor, often the building owner, pays a monthly fee until the costs are paid off. The contractor recoups its costs and makes a profit on the monthly fee; the investor, or occupier, saves money over the long term. Various contract models exist (guaranteed saving, shared saving, credit risk insurance). Energy service companies are currently used most commonly in industrial and nonresidential buildings (IEA 2018) and are suitable primarily for energy-saving investments (Urge-Vorsatz et al. 2020).

Enhance institutional capacity to accelerate the transition

If regulations are put in place and enforced, demand for zero-carbon buildings could increase rapidly (IPCC 2022b). Putting them in place will require substantial changes to practices throughout the system, from the design of buildings, to their construction methods, to the provision of financial services. All actors in the built environment will need enhanced, or modified, institutional capacity to enact these changes.

The first step is to enforce building regulations to ensure that they are effective. Enforcement includes monitoring and issuing penalties for noncompliance. Penalties may be financial; they can also include options such as retraction of permits for leasing. Sufficient capacity is needed for regulatory organizations to be effective. Regulators need to have sufficient funds and personnel for monitoring, and personnel require appropriate training on new and changing regulations.

To change practices and comply with regulations, builders, contractors, architects, engineers, and other built environment actors all require skills and training on zero-carbon buildings (IEA 2019b; IPCC 2022b). Retraining is an essential part of ensuring a just and equitable transition in the buildings sector as traditional fossil-based technologies are phased out and skill sets for installation and maintenance become redundant. Governments can support initial training programs until the market grows and increases incentives for individuals to develop appropriate skills.

Establish and implement decarbonization roadmaps

Governments can show leadership by making commitments toward decarbonization, outlining visions and plans, making first moves, and providing additional support to early moving projects (GlobalABC et al. 2020; Climate Action Tracker 2022a). The GlobalABC roadmap outlines what these visions and plans could look like in detail for urban planning, new and existing buildings, appliances, construction materials, and more, with key milestones that need to be achieved and progressive development in the coming decades (GlobalABC et al. 2020).

Many governments and businesses are signaling their intent to shift to low-carbon buildings by signing declarations and commitments, such as the World Green Building Council's Net Zero Carbon buildings commitment, which now has over 170 signatories from businesses, states, and cities (WGBC 2021). Those that have signed up will now need to translate that commitment into action on the ground. Some cities, such as Ithaca, New York (United States); and Vancouver, British Columbia (Canada), have demonstrated that concerted effort can stimulate change.

SECTION 4

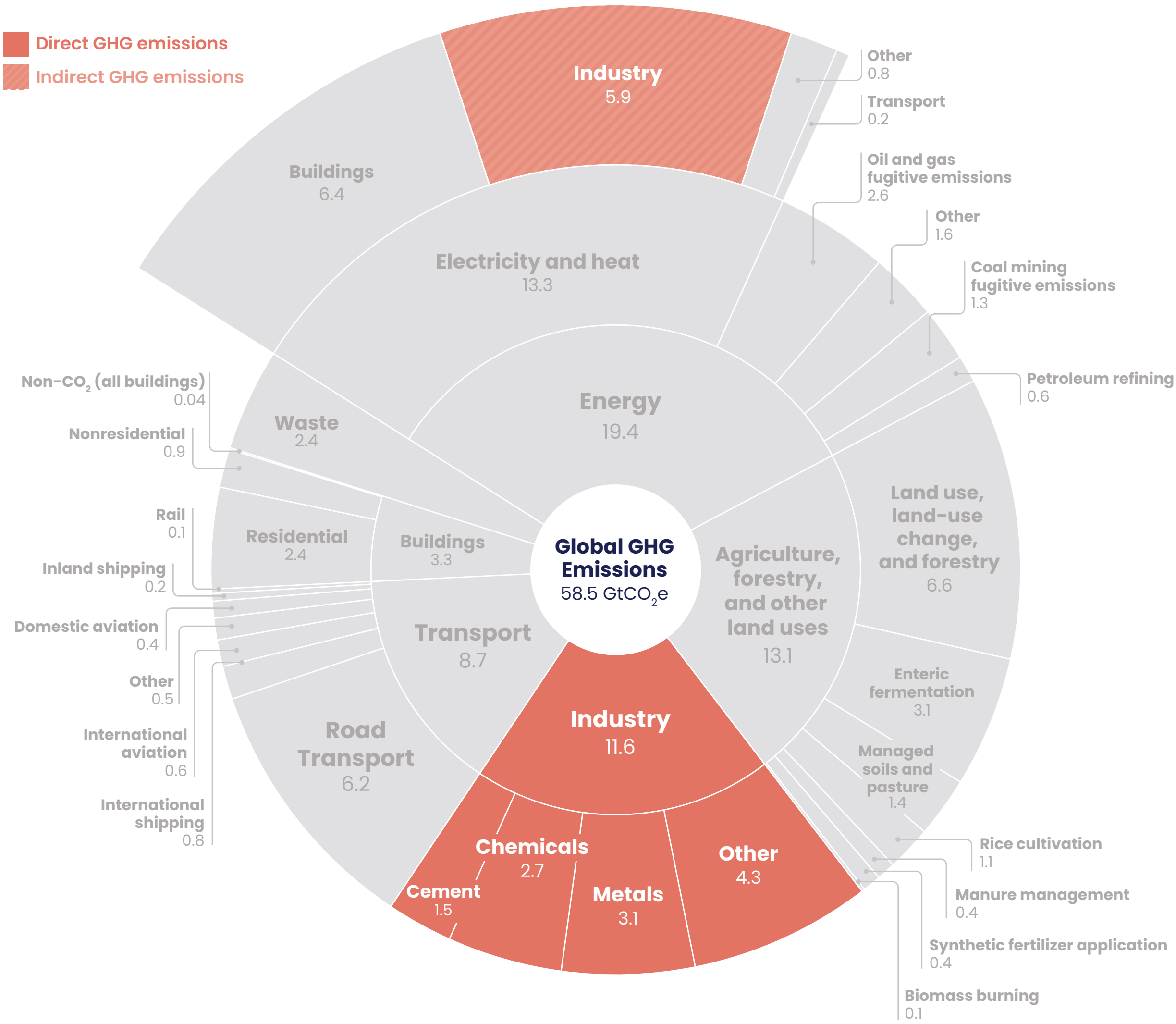
Industry

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. When accounting for both "direct" energy-related GHG emissions from fossil fuel combustion and industrial processes (e.g., the chemical reactions involved in creating cement) as well as "indirect" GHG emissions from power and heat generation used to drive these processes, this system emits roughly 18 gigatonnes of carbon dioxide equivalent ($GtCO_2e$) annually (Figure 19).[18] Direct GHG emissions alone reached almost 12 $GtCO_2e$ in 2019, representing about a fifth of global emissions (IPCC 2022b). Decarbonizing industry, then, must play a critical role in limiting warming to 1.5°C.

Yet total GHG emissions from industry have risen faster than in any other system since 2000 (Figure 20). Increasing demand for industrial products, driven by

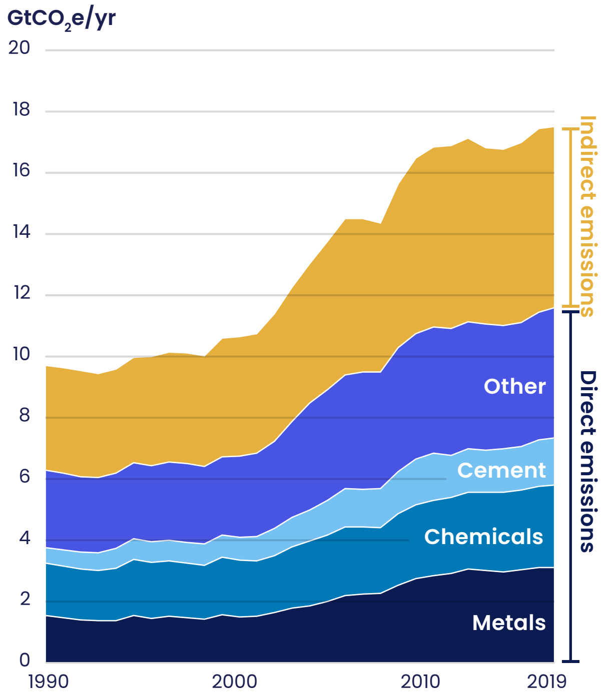
rising rates of prosperity, urbanization, and infrastructure development, has fueled significant growth in the extraction and production of materials around the world. Indeed, industrial expansion accounted for 45 percent of worldwide growth in GHG emissions over the last two decades (Lamb et al. 2021; IPCC 2022b). Annual growth in industrial GHG emissions did slow from 4.3 percent between 2000 and 2010 to 1.5 percent between 2011 and

FIGURE 19 | Industry's contribution to global GHG emissions in 2019



Notes: CO_2 = carbon dioxide; GHG = greenhouse gas; $GtCO_2e$ = gigatonnes of carbon dioxide equivalent.
Source: Minx et al. (2022), described in Minx et al. (2021) and used in IPCC (2022b).

FIGURE 20 | 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. "Other" includes a range of manufacturing processes, such as those for pulp and paper, food and tobacco, and glass and ceramics. *Source*: Minx et al. (2022), described in Minx et al. (2021) and used in IPCC (2022b).

2019, as it followed periods of global economic expansion (until 2008) and recession and recovery (Minx et al. 2021). Moreover, in 2020, CO_2 emissions from the industry system specifically fell by another 179 million metric tons (Mt) as governments around the world adopted measures to reduce the spread of COVID-19 (Sikarwar et al. 2021). Preliminary 2021 data, however, suggest that this decline was temporary, with these emissions already rebounding (Davis et al. 2022).

Transforming industry to achieve the deep GHG emissions cuts required to hold global warming to 1.5°C entails three critical shifts. First, significantly increasing energy productivity, which reduces energy use while maintaining services, not only can help reduce this system's GHG emissions but also can lower the total amount of energy consumed across industry that would otherwise need to be decarbonized. This must be achieved through technical energy efficiency, material efficiency, and service efficiency (ETC 2020). Second, electrification with a clean grid 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. Thus, decarbonizing these processes requires strategies such as switching to new fuels to deliver high heat, developing technologies to eliminate process emissions altogether and/or reliance on high heat, and using conventional technologies with carbon capture, utilization, or storage (CCUS).

Accelerating these shifts across all cement and steel production—the two industrial processes examined in depth in this report (Table 4)[19]—will prove especially critical in the coming decades, as both are among the most

TABLE 4 | Summary of global progress toward industry targets

INDICATOR	MOST RECENT DATA POINT (YEAR)[A]	2030 TARGET	2050 TARGET	TRAJECTORY OF CHANGE	ACCELERATION FACTOR	STATUS
Share of electricity in the industry sector's final energy demand (%)	28 (2020)[a]	35	40–45 (2040) 50–55 (2050)		1.7x	
Carbon intensity of global cement production ($kgCO_2$/t cement)	656 (2019)	360-370	55–90		>10x	
Carbon intensity of global steel production ($kgCO_2$/t steel)	1,890 (2020)	1,335–1,350	0–130		N/A; U-turn needed	
Green hydrogen production (Mt)	0.023 (2020)	81	320		>10x	

Notes: $kgCO_2$/t = kilograms of carbon dioxide per tonne; Mt = million tonnes.

[a] Data for this indicator are not publicly available and were accessed with paid licenses to datasets or with permission from the data provider.

Sources: Historical data from IEA (2021q), GCCA (2021), World Steel Association (2021a), and IEA (2021e); targets from Climate Action Tracker (2020b) and IEA (2021h).

difficult industries to decarbonize and, together, are responsible for more than half of direct GHG emissions from industry (ClimateWatch 2022). Tracking the carbon intensity of cement and steel production, specifically, reflects improvements in energy efficiency, progress in electrification, and adoption of low-carbon technologies for processes that cannot be electrified.

Status of industry indicators

INDUSTRY INDICATOR 1:

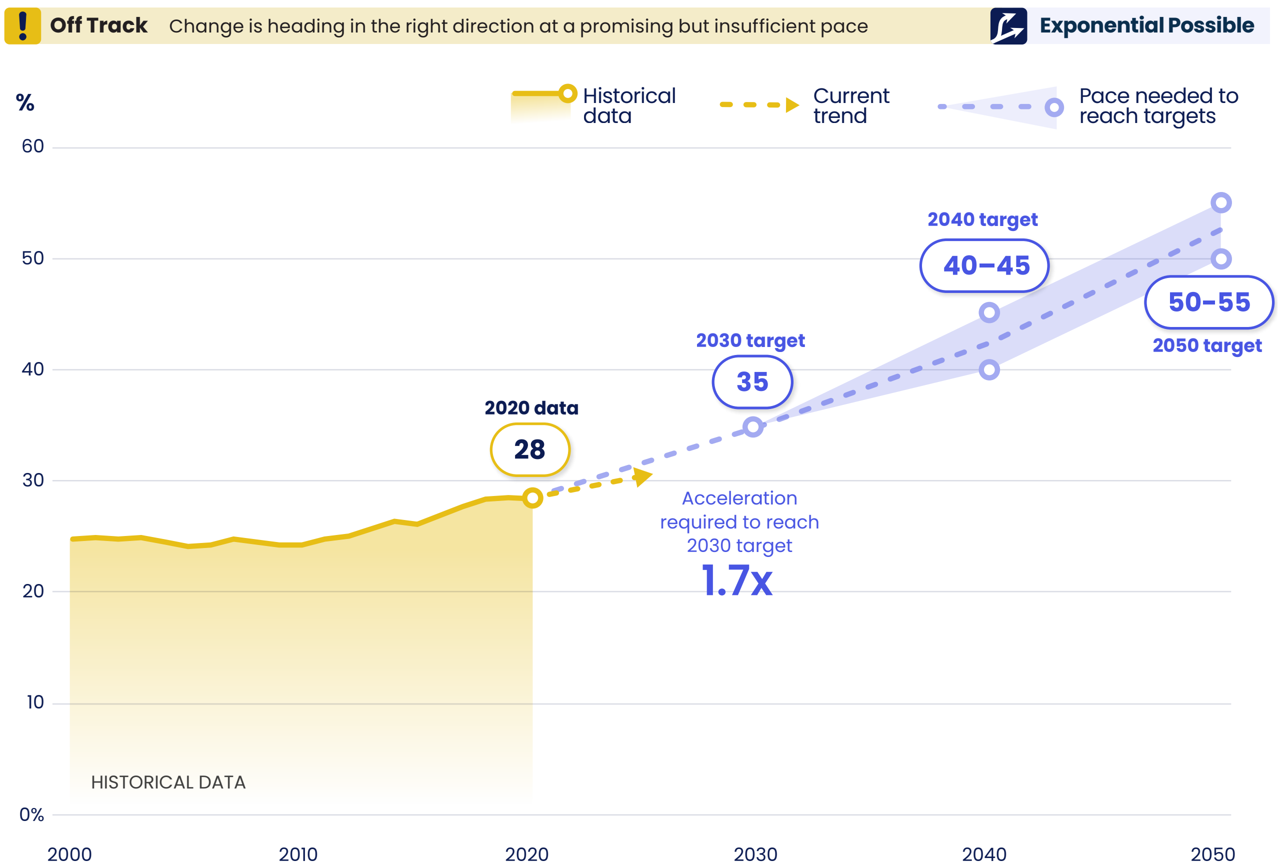
Share of electricity in the industry sector's final energy demand (%)

- **Target**: The share of electricity in the industry sector's final energy demand increases to 35 percent by 2030, 40–45 percent by 2040, and 50–55 percent by 2050.

Many industrial processes still depend on fossil fuels, although this long-term trend may be shifting. From 2016 to 2020, the share of electricity in the industry system rose from 26.9 percent of the system's final energy demand to 28.4 percent, growing at 0.4 percent per year on average (Figure 21). Even though that rate is still insufficient to reach the 1.5°C-aligned near-term target for 2030, it is not far off and would need to accelerate by a factor of 1.7.

Global efforts toward achieving the near-term target for this indicator are off track, despite regional differences in electrification rates. As displayed in Table 5, across Europe, Oceania, and Asia, the share of electricity in industry's final energy demand was close to or above the global average of 28 percent in 2019. The electrification rate in Asia, for example, grew from 25 percent to 29 percent between 2015 and 2019, while the rate remained relatively stable in all other regions except in the Middle East, which increased but was far below the global average, at just 13 percent in 2019 (IEA 2021q). Some form of rapid, nonlinear growth in electrification across these regions may be possible in the medium to long term, particularly as technologies to electrify or eliminate high-temperature processes come to market

FIGURE 21 | Historical progress toward 2030 and 2050 targets for the share of electricity in the industry sector's final energy demand



Sources: Historical data from IEA (2021q), accessed with a paid license to the IEA's datasets; targets from Climate Action Tracker (2020b).

TABLE 5 | Share of electricity in the industry sector's final energy demand across regions

	2016	2017	2018	2019	2020
Africa	25%	25%	25%	25%	26%
Americas	27%	27%	26%	27%	26%
Asia	26%	28%	29%	29%	29%
Europe	29%	29%	30%	30%	29%
Middle East	11%	12%	13%	13%	13%
Oceania	29%	29%	29%	29%	29%
World	27%	28%	28%	28%	28%

Source: Data derived from IEA (2021q), accessed with a paid license to the International Energy Agency's datasets.

and as clean electricity prices continue to decline (while gas price spikes render electrification even more economical). But achieving such rapid, nonlinear change will require appropriate support from government and the private sector.

INDUSTRY INDICATOR 2:
Carbon intensity of global cement production ($kgCO_2$/t cement)

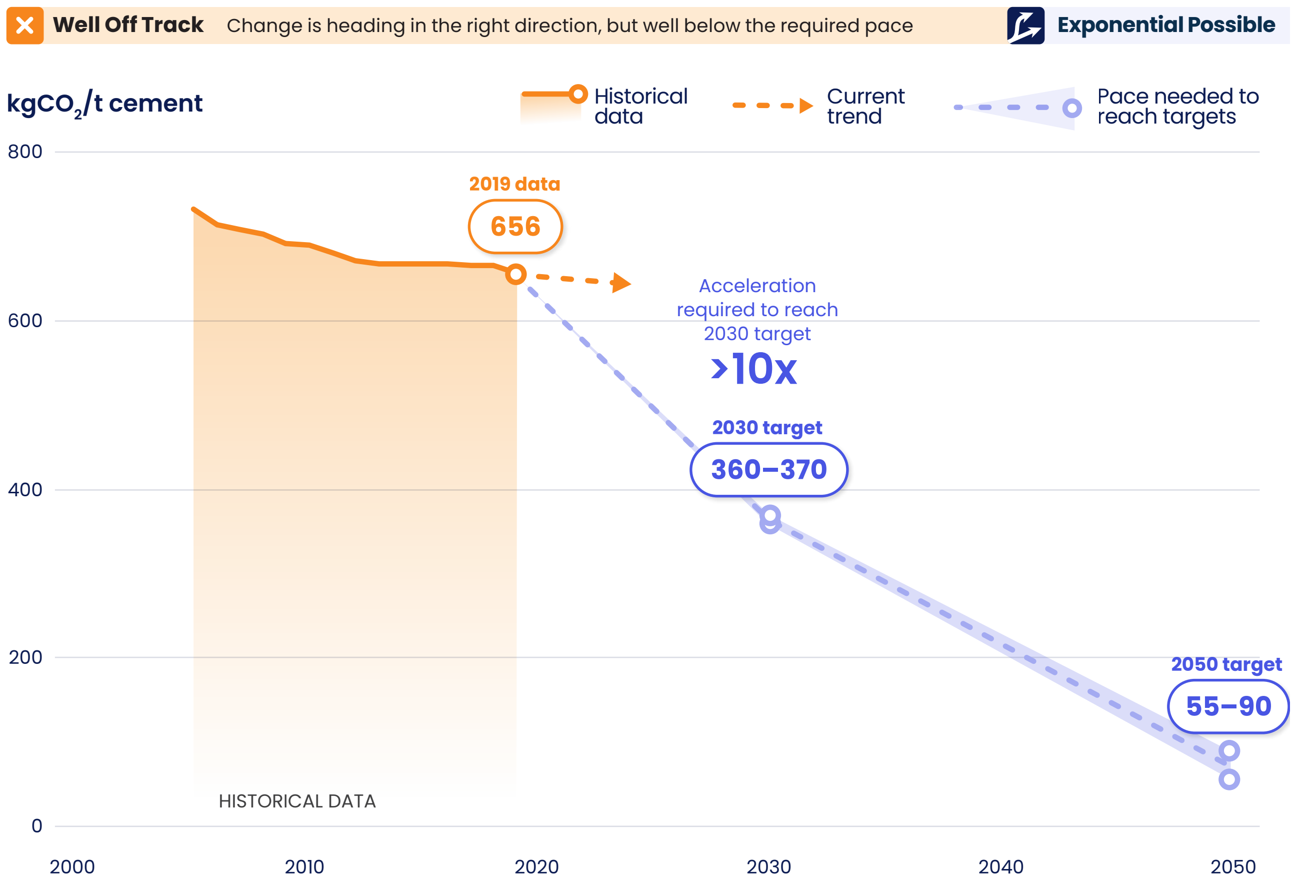
- **Targets**: The carbon intensity of global cement production declines to 360–370 kilograms of carbon dioxide per tonne ($kgCO_2$/t) of cement by 2030 and 55–90 $kgCO_2$/t of cement by 2050, with an aspirational target to achieve 0 $kgCO_2$/t of cement by 2050.

Decarbonizing the production of cement—one of the world's most energy-intensive and in-demand construction materials—poses a major challenge to holding global warming to 1.5°C. From 1990 to 2019, new facilities for cement production built primarily across emerging economies fueled significant global growth in CO_2 emissions. In the Middle East, Asia, and Africa, for example, CO_2 emissions rose by an average of 4.5 percent each year during this period, mainly as a result of rapid urbanization and industrialization (Chen et al. 2022).

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 gains made across the technological equipment used for cement production have reached nearly maximum attainable rates. Reductions in the clinker-to-cement ratio[20]—defined as the amount of clinker (the "glue" that binds the raw materials of cement together) used per metric ton (tonne) of cement—did drive reductions in carbon intensity of cement between 2018 and 2019. These advances, however, do not necessarily reflect greater efforts to decarbonize cement production, as the clinker-to-cement ratio may vary for a several disparate reasons, including the availability of supplementary cementitious materials and the desired strength of the concrete.

Achieving additional reductions instead will require an acceleration of action and a more ambitious portfolio of mitigation strategies, including those that promote demand reduction, improved efficiency, switches to alternative fuels, novel cement chemistries, use of CCUS and associated infrastructure, and kiln electrification. Should recent progress continue at its current pace, the carbon intensity of global cement production would decrease only marginally, falling far short of meeting its 1.5°C-aligned 2030 and 2050 targets (Figure 22). To align with a 1.5°C pathway, improvements in carbon intensity must increase more than 10 times faster.[21] It is important to note here that rapid, nonlinear change is possible,

FIGURE 22 | Historical progress toward 2030 and 2050 targets for the carbon intensity of global cement production



Note: $kgCO_2/t$ = kilograms of carbon dioxide per tonne.
Sources: Historical data from GCCA (2021); targets from Climate Action Tracker (2020b).

particularly if zero-carbon cement technologies and CCUS come to market and begin to diffuse with ample support in the form of policies, finance, and industry leadership coupled with demand signals.

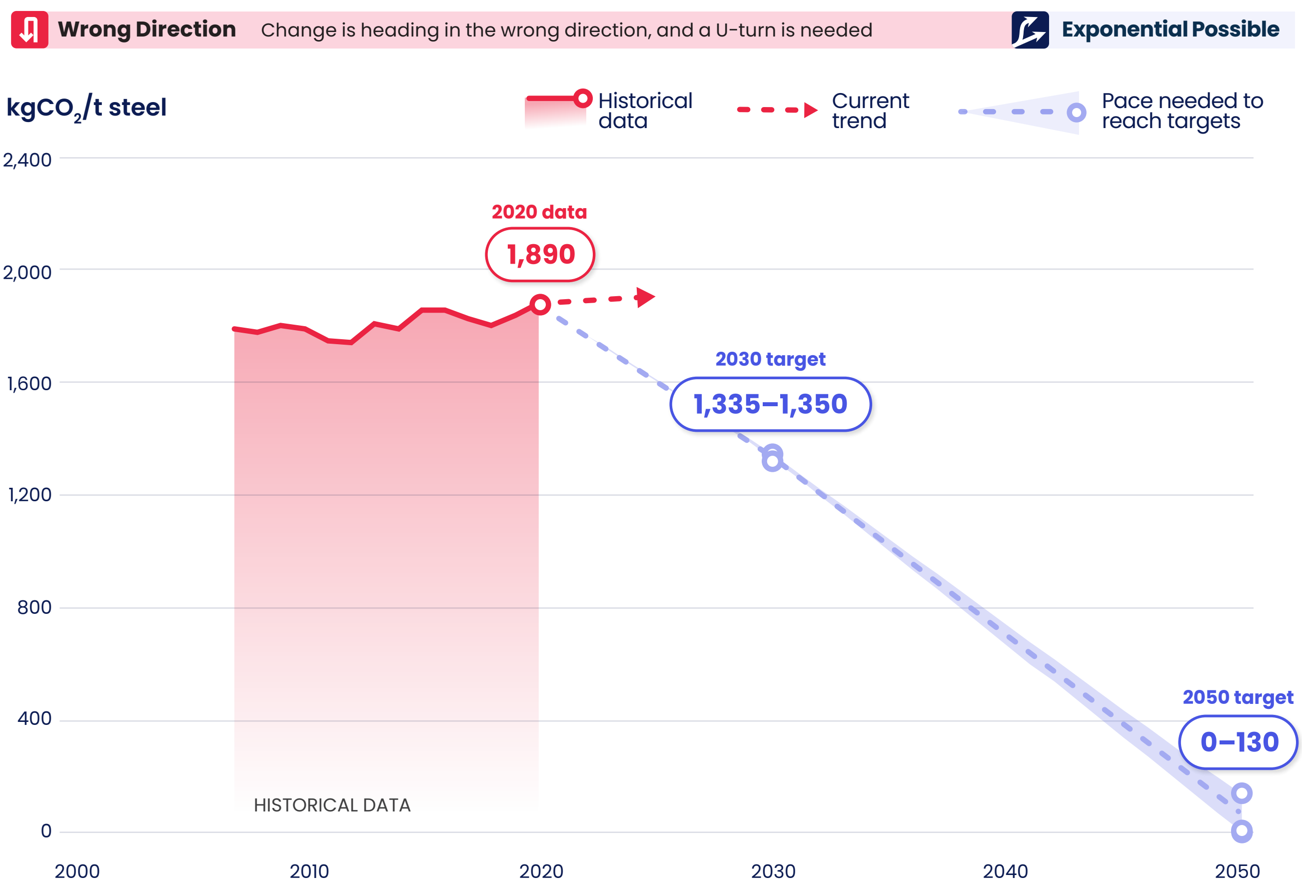
INDUSTRY INDICATOR 3:
Carbon intensity of global steel production ($kgCO_2/t$ steel)

- **Targets**: The carbon intensity of global steel production declines to 1,335–1,350 $kgCO_2$ /t of steel by 2030 and 0–130 $kgCO_2$ /t of steel by 2050.

Available data from the World Steel Association show that the carbon intensity of steel production has remained fairly steady over the past five years, declining by 1 percent annually between 2015 and 2018 and then rising by 2 percent annually from 2018 to 2020 (Figure 23). Growth in the share of blast furnace–based steel production in China, which currently manufactures roughly half of the world's steel, has likely fueled much of this recent global increase in carbon intensity. These furnaces rely primarily on coke and generate the majority of CO_2 emissions from steel production (World Steel Association 2020, 2021b; Nicholas and Basirat 2021). Accordingly, in China and other major steel-producing countries, recent efforts to decarbonize steel production are heading in the wrong direction. Limited availability of scrap steel is a key reason that the shift toward electric arc furnace (EAF)–based steelmaking—which uses scrap and is less emissions-intensive—has not been realized yet. EAF steelmaking can also use iron processed using direct reduced iron (DRI) technology (Ellis and Bao 2020).

If the average rate of change between 2016 and 2020 were to continue, the carbon intensity of global steel production would keep rising and place 1.5°C-aligned targets for both 2030 and 2050 further out of reach. Changing this course will require that a far greater share of steel production rely on technologies such as scrap-based EAF, green hydrogen-based DRI, iron ore electrolysis, and deploying CCUS-equipped process technologies (IEA 2021h).

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



Note: kgCO_2/t = kilograms of carbon dioxide per tonne.
Sources: Historical data from World Steel Association (2021a); targets from Climate Action Tracker (2020b).

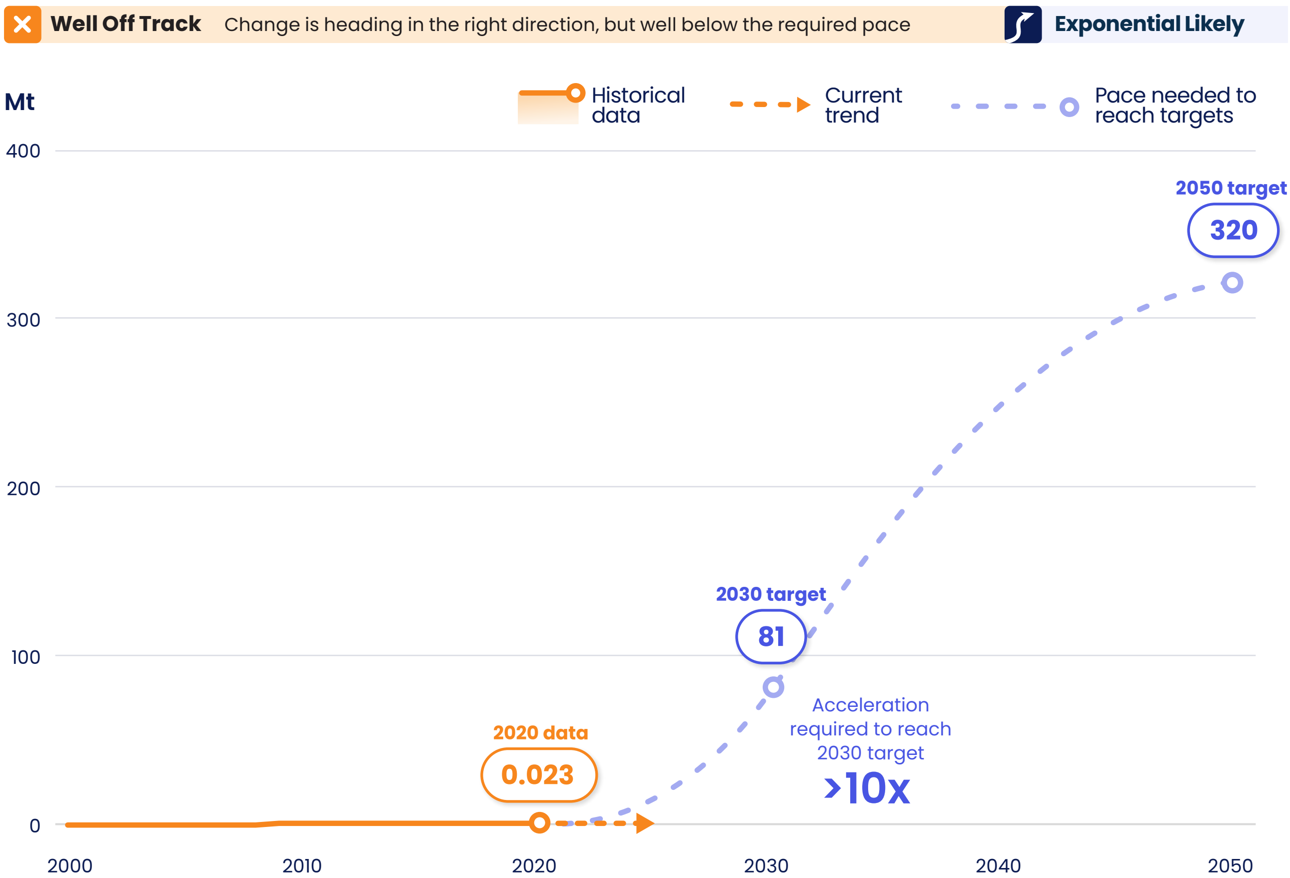
INDUSTRY INDICATOR 4: Green hydrogen production (Mt)

- **Targets**: Green hydrogen production capacity reaches 81 Mt by 2030 and 320 Mt by 2050.

Hydrogen is currently used primarily as a chemical feedstock in industrial processes (for example, to produce ammonia) and is increasingly in demand across industry, including in steel production and in other processes that require high-temperature heat. To date, the production of hydrogen has relied almost exclusively on fossil fuels, mainly natural gas, and, accordingly, has contributed to the system's increasing GHG emissions. Green hydrogen, which is produced through electrolysis[22] using clean electricity, offers an alternative, zero-carbon fuel.[23] But as an emerging technology, green hydrogen cannot yet meet global demand for hydrogen, particularly in industry. Green hydrogen accounted for just 0.03 percent of hydrogen production in 2020 (IEA 2021e). Transitioning to a 1.5°C pathway will require green hydrogen use to grow rapidly, reaching 81 Mt in 2030 and 320 Mt in 2050 (Figure 24). The corresponding electrolyzer capacity required in 2030 is estimated at up to 850 GW (IEA 2021e)—Comparing to the total installed renewable energy installments in 2021 of roughly 3,000 GW (Lebedys et al. 2022), reaching that goal will require a steep increase in renewable energy installments, which is explored in Section 2.

Recent historical data indicate that global efforts to scale up green hydrogen production are well off track and require substantial acceleration to hold global warming to 1.5°C. Indeed, although global green hydrogen production has increased rapidly in recent years, from 0.003 Mt in 2010 to 0.023 in 2020, this recent rate of progress needs to increase by more than 10 times to reach 81 Mt by 2030. However, because green hydrogen is the type of innovative technology that often follows an S-curve, and the technology is in the emergence stage of adoption, the rate of change will likely be faster in the future than in the past five years, should the technology receive appropriate support from decision-makers across government and the private sector, which is not guaranteed.

FIGURE 24 | Historical progress toward 2030 and 2050 targets for green hydrogen production



Note: Mt = million tonnes.
Sources: Historical data derived from IEA (2021e); targets derived from IEA (2021h).

Global assessment of progress for industry

Given industry's significant and growing contribution to global GHG emissions throughout the 21st century, decarbonizing industrial processes will underpin efforts to hold global warming to 1.5°C. 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 to maximize energy efficiency, achieve circularity in production and consumption, electrify industrial heat, and develop new fuels, feedstocks, and technologies to decarbonize industrial processes that cannot easily be electrified—particularly those in the system's highest-emitting industries: cement and steel.

Critically, many industries in the industry system at large still need to maximize energy efficiency gains. Although many existing technologies have already achieved the highest possible efficiencies, deployment of these innovations remains uneven (ETC 2018a). To date, many developed countries have reduced carbon intensities in industry primarily by scaling up the adoption of best available technologies. But in many developing countries, best available technologies have yet to achieve widespread diffusion. Reaching similar rates of adoption across these nations, then, can help improve energy efficiency and deliver near-term GHG emission reductions. Although such gains may make a relatively low contribution to climate change mitigation globally, they are nonetheless essential in decarbonizing the system. Further, material efficiency and circularity continue to lag as policy priorities and need to be mainstreamed through a mix of instruments and regulations to incentivize efficient resource use (Hertwich et al. 2020).

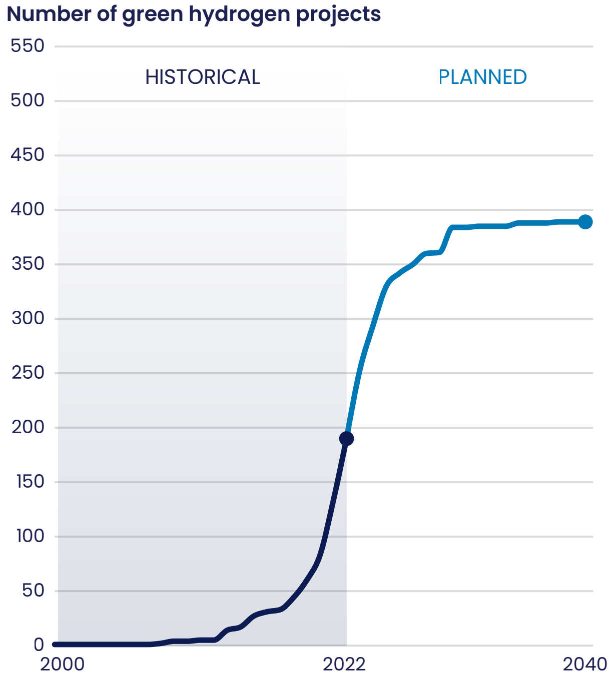
In addition to optimizing energy efficiency wherever possible, industries should dramatically increase electrification of low- and medium-temperature heat processes—a strategy that is only effective in decarbonizing industry when implemented alongside measures that reduce the carbon intensity of power generation (see Power Indicator 1). Historically, industrial companies have focused on electrifying nonheating industrial operations, including machinery like pumps, robotic arms, and conveyor belts. These efforts have caused the global rate of electrification to grow at a steady pace in recent years. But there is now room for electrifying a much wider range of industrial processes in the near term, as, to date, companies have electrified only a small share of those that rely on a low to medium amount of heat (Roelofsen et al. 2020) (for instance, heat used for processes in the chemical subsector). Many technologies that can help increase electrification of low- and medium-heat processes are already commercialized and readily available for adoption. McKinsey, for example, estimates that electricity could replace almost 50 percent of fuel in industry by adopting existing best available technologies (Roelofsen et al. 2020).

But for high-temperature processes (those that require temperatures of more than 1,000°C), electrification, although technically possible, still requires further development. In the meantime, new fuels and technologies will be needed both to replace fossil fuels in generating high heat and to reduce industry's reliance on processes that require extreme temperatures. Recent innovations in cement production, for example, show that renewables could replace fossil fuels in directly generating the high-temperature heat that clinker kilns need. In early 2022, for instance, CEMEX and Synhelion announced the successful operation of the world's first clinker kiln using concentrated solar radiation.

Another relatively new fuel, green hydrogen produced through electrolysis, can be used as a chemical feedstock to reduce process emissions and fulfill the need for high-temperature heat. Although progress made toward reaching 81 Mt annual green hydrogen production by 2030 remains well off track, the number of planned hydrogen electrolyzer projects is increasing rapidly (Figure 25). Bloomberg New Energy Finance (BNEF), for example, estimates that electrolyzer sales will quadruple by the end of 2022, driven by growing political support and an increasing demand for green hydrogen led by the heavy industry. However, because of the energy efficiency losses that occur when producing green hydrogen, direct electrification remains the most efficient option in most industrial processes. Accordingly, companies should employ green hydrogen only where electrification is not possible, while also considering that the latter approach will require adequate clean energy capacity and associated transmission and distribution infrastructure.

Green hydrogen can also play a particularly important role in eliminating process emissions in steel production, which account for a major share of steel's carbon intensity and are particularly challenging to reduce. Specifically, it can act as a carbon-free reduction agent in the production of iron, which companies further process into steel by using electricity in an electric arc furnace. Doing so removes the need for the coal-fired blast furnaces that the industry typically uses. To date, planned low-carbon steel facilities indicate a clear preference for hydrogen-based steel production, though these are mostly European companies and the balance will only shift globally when China adopts a similar trend (Figure 26). But even though the number of

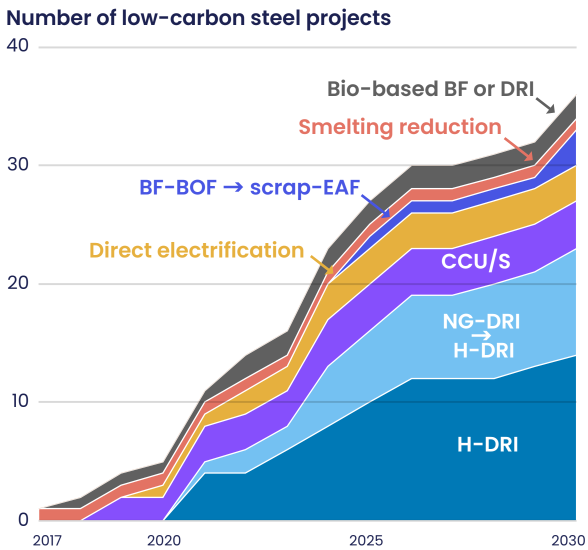
FIGURE 25 | Number of cumulative green hydrogen projects globally put into operation and to become operational according to current planning



Notes: Seven reported projects without stated years by which to become operational are excluded from this figure. The number of projects excludes those fed by grid and nuclear electricity, as well as those with unknown years by which to become operational.

Source: Derived from IEA (2022d).

FIGURE 26 | Number of cumulative low-carbon steel projects by technology type and year planned to become operational



Notes: BF-BOF = blast furnace to basic oxygen furnace; CCU/S = carbon capture and usage or storage; EAF = electric arc furnace; H-DRI = hydrogen-based direct reduced iron; NG=DRI = natural gas-based direct reduced iron.

Sources: Data derived from the Green Steel Tracker (based on data last updated in November 2021), complemented by authors' research (Leadit 2021). Only projects with a known expected date to be put in operation are included.

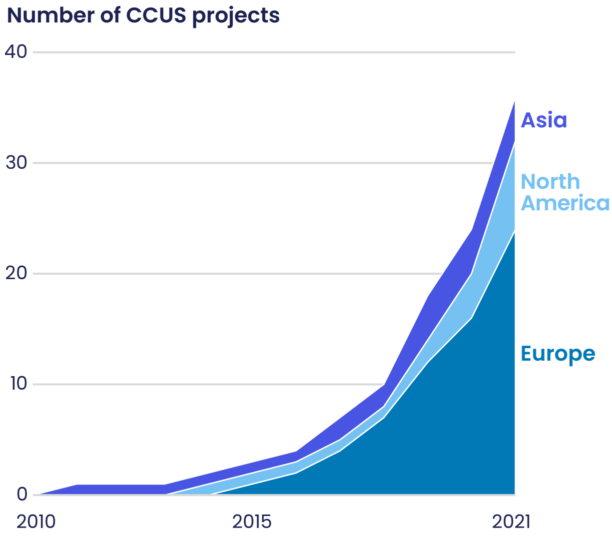
low-carbon steel facilities is increasing—an estimated 30 will become operational by 2030—the build-out of new coalfed blast furnace capacities is increasing at a more rapid pace, with 23 plants under construction and 50 proposed.[24] The increasing share of blast furnaces in steel production capacity is likely one of the key drivers behind the rise in carbon intensity of global steel production, and, as a result, equipping these facilities with CCUS technology will remain a mitigation option as well (IEA 2021h).

As in steel production, process emissions in cement production are also responsible for over half of cement's carbon emission intensity (about 60 percent), which has decreased only marginally in recent years. Cement companies could, in theory, reduce or even eliminate these GHG emissions by producing ordinary cement[25] or novel cements using materials that generate significantly lower or no process emissions. To date, however, novel cements have struggled to enter the market due to various barriers. These include the sector being dominated by several companies that are reluctant to take the lead in developing new products, little economic incentive to reduce emissions from the industry in the short term, slow processes for updating concrete standards, the construction industry's skepticism about new cements being able to serve the same function as ordinary cement and meet industry standards, and higher cost for buyers.

Due to various technological and economic challenges associated with eliminating process emissions, decarbonizing industry will likely require significant amounts of CCUS. For cement, in particular, technological options for decarbonizing production are limited, and raw material availability may constrain the potential of alternative cements. Most decarbonization pathways in the literature suggest that cement production, then, will to a large extent rely on CCUS retrofits (Paltsev et al. 2021; Global Climate Action 2021; Climate Action Tracker 2020b; ETC 2019a). Globally, the number of announced cement-related CCUS projects is on the rise (Figure 27). Europe is leading in terms of the number of projects, followed by North America and Asia. However, more information is needed to gauge whether current efforts are in line with a 1.5°C-compatible trajectory.

Ultimately, because of the aforementioned challenges associated with decarbonizing both steel and cement processes, retrofits or major refurbishments to existing cement and steel facilities will be imperative to transforming the industry system at large. Large technology stocks of relatively young, coal-reliant production capacity will have to be refurbished or prematurely retired to eliminate emissions. This will be particularly important in China, where the majority of global steel and cement is produced.

FIGURE 27 | Number of cumulative CCUS projects in the cement sector by year of announcement



Note: CCUS = carbon capture, utilization, or storage.

Sources: Projects are collected from various sources, including GCCA (2021), Lyons et al. (2021), and Plaza et al. (2020). The database is not exhaustive but gives an indication of the overall trend.

Accelerating these shifts to decarbonize industry will likely have implications for communities that rely heavily on industrial plants for employment. Depending on the industry, large plants can employ several thousand people (typically more in steel plants than in cement plants), providing jobs to a large share of the local population. However, because decarbonization will require a secure and ample supply of renewable energy, industrial plants may need to move from the source of the raw material to a location with a higher renewable energy capacity (de Pee et al. 2018).[26] What's more, the adoption of new technologies may require new skills and, accordingly, retraining programs for workers. Minimizing the potential adverse impacts of these measures will likely require early planning and support for communities to reskill and diversify their employment portfolio (e.g., unemployment insurance, government-funded training programs, dedicated funds for economic diversification and revitalization, etc.), as well as long-term decarbonization roadmaps developed with meaningful participation from a wide range of stakeholders, including workers, employers, communities, civil society organizations, and governments (Rissman et al. 2020).

Enabling conditions for climate action across industry

Achieving industrial decarbonization aligned with the Paris Agreement's 1.5°C temperature goal requires a wide range of technical, financial, and political interventions to overcome barriers. These include the implementation of comprehensive policies to spur deep emissions cuts across industry, ambitious targets to speed up commercialization, strong implementing institutions, and investments at a desired scale to develop clean technologies and build new infrastructure for renewables and green hydrogen (Rissman et al. 2020; IEA 2021e). While the conditions that enable transformational change across industry vary by context, the following measures can help nations surmount the obstacles at hand, and enable exponential growth.

Enhance production of low-carbon industrial products through carbon pricing, public procurement policies, and standards

The increasing number of economy-wide net-zero goals from governments supported by adoption of ambitious short- and medium-term policies is likely to provide a favorable environment for industrial decarbonization policies (IEA 2021t). Yet a lack of comprehensive, well-designed policies targeting industry-wide decarbonization, from mandating energy efficiency improvements, to encouraging electrification of industrial processes, to incentivizing innovation, leaves the system behind in terms of 1.5°C alignment.

Carbon pricing through emissions trading or carbon taxes—along with provisions that maintain industrial competitiveness and address carbon leakage—represents a key policy intervention for industrial decarbonization. Given the right price,[27] such a mechanism can incentivize low-carbon action, like adopting best available technologies to improve energy efficiency, and drive innovation in new technologies such as novel cements to reduce process emissions (World Bank 2021). In 2021, China, which is responsible for almost 30 percent of global manufacturing output (Richter 2020), joined the growing number of countries with an emissions trading system (ETS), creating the largest carbon market in the world. China's ETS currently covers the power sector, with cement and aluminum likely to be included in the future (*Carbon Pulse* 2021). The country also requires key energy-intensive industries, such as steel and paper, to report emissions. Improved data on industrial emissions, which account for almost 60 percent of China's total emissions, are likely to support future inclusion of more sectors in China's ETS (Reuters Staff 2020; Liu et al. 2019).

Addressing any adverse economic and social effects of carbon markets on consumers and vulnerable communities is crucial for successful climate action. Indeed, carbon pricing policies need to be designed to mitigate any unintended negative economic and social impacts on communities through social safety nets and other measures. These may include cash transfers, reduced taxes, unemployment insurance, government-funded training programs, reemployment services, and dedicated funds toward economic diversification and revitalization, among others (Rissman et al. 2020; Shang 2021).

Beyond carbon pricing, governments, as one of the main consumers of industrial goods, can also incentivize companies to produce low-emissions materials. In the United States, for instance, approximately 18 percent and 50 percent of annual CO_2 emissions associated with steel and cement consumption, respectively, are associated with public construction (Hasanbeigi et al. 2021). Green or sustainable procurement policies that require public entities to purchase low-carbon industrial products at a premium create a guaranteed market for these products. These policies therefore reduce the financial risks of transitioning from conventional, emissions-intensive production processes to those that are more aligned with

a 1.5°C pathway (Bataille 2019). As industries increase production to meet growing demand, they may eventually reach economies of scale, whereby the costs of creating each additional tonne of cement or steel decrease as the total amount produced rises (UNEP 2017; Hasanbeigi et al. 2019; Hasanbeigi et al. 2021).

This year, Germany announced carbon-based premiums for steel, cement, lime, and ammonia industries (Hillemann and Ehls 2022), while the European Commission is currently considering adopting them (Hall 2021). In the United States, California has set up a "Buy Clean" green procurement program for infrastructure materials, such as steel. The program is likely to positively impact markets for these products and influence the design of other procurement programs across the United States (Krupnick 2020). Similarly, in 2021, the United Kingdom, India, Germany, the United Arab Emirates, and Canada pledged to buy low-carbon steel and concrete under the Industrial Deep Decarbonization Initiative. This initiative aims to encourage at least 10 governments to commit to low-carbon steel and cement procurement within the next three years, which could have a significant impact if aimed at the top-producing countries (UNIDO 2021). Large-scale private consumers can play a similarly outsized role in stimulating demand for low-carbon industrial products through private buyers' coalitions, such as the First Movers Coalition (2022), which is aggregating the purchasing power of over 50 companies to commercialize zero-carbon technologies in hard-to-abate sectors.

Governments should also use other policy tools, as complementary programs are needed to move clean technologies along the S-curve from emergence to diffusion to the widespread adoption phase. These mechanisms may include tax credits to support emerging technologies reach cost parity, directly mandating industrial companies to adopt new technologies (e.g., revising construction codes to require a certain share of low-carbon cement), or introducing low-carbon product standards that set an emissions intensity benchmark (e.g., low-carbon cement with novel chemistries) (Cao et al. 2021; Fransen et al. 2021; Saha et al. 2021).

Put in place regulations to increase energy efficiency

Much of the remaining energy efficiency–related improvements need to occur in developing countries and economies in transition,[28] where many industries rely on relatively inefficient equipment and where much of the growth in energy demand is expected. Currently, for instance, mandatory efficiency standards apply to just 40 percent of global energy consumption by industrial motors, and this coverage is even lower in Africa, where industrial production is growing (Vass et al. 2021). Distorted energy prices due to subsidies (such as on fossil fuels), lack of capacity (e.g., institutional, technical, and human capacity), and limited access to capital are among the key barriers to increasing energy efficiency across industry (Olsthoorn et al. 2016; Rissman et al. 2020). A combination of policy programs, such as energy intensity targets, information and training, energy audits, digital management systems, and financial incentives, can help overcome these obstacles. Examples of such measures include India's Perform, Achieve, and Trade scheme and China's Top 1,000 and Top 10,000 programs. The impact of those, however, needs to be further evaluated. Finally, emphasis on effective implementation of existing policies and mandates in developing countries is as critical as adopting more ambitious regulations, given a lack of strong institutions to enforce regulations in these countries (Olsthoorn et al. 2016).

Make it cost-competitive to electrify industry using renewable energy

Electrification of industry at a massive scale using renewable electricity will provide a big mitigation wedge for the system. Indeed, existing technologies can electrify almost 50 percent of fuel used by industry to provide energy (Roelofsen et al. 2020). But electrification is only financially attractive when operational costs are lower—in other words, when electricity is cheaper than fossil fuels used in conventional equipment. Declining costs of renewable electricity are supportive of this objective, but a price on carbon and/or removing fossil fuel subsidies can further improve the cost-competitiveness of renewable-based electricity. Further research and development to improve the energy efficiency of electric equipment (so that less electricity is needed to run the equipment) can also lower the operating costs and render it increasingly financially attractive to electrify (Roelofsen et al. 2020).

Increase investments in low-carbon industrial technologies

The level of decarbonization needed in industry will require substantial investment in low-carbon technologies to reduce process emissions and reliance on fossil fuels to generate high-temperature heat—as much as $5 trillion through 2050, according to one estimate (IRENA 2018). Additional support is therefore needed to further develop technologies in the early development stage, such as new methods to directly electrify steel production, high-temperature heat for cement production, and new low-carbon cement chemistries. Moreover, investments are needed to prove more developed technologies at scale, such as CCUS and the transportation and storage of captured CO_2, as well as green hydrogen-based steel production.

Green hydrogen, specifically, is currently up to over four and a half times more expensive than gray hydrogen produced from natural gas, given high costs of power and electrolyzer production (IEA 2021e). The good news is that declining costs of renewables will likely make green hydrogen cheaper (see Section 2), while gray hydrogen costs are likely to increase with rising natural gas prices (Hare et al. 2021). In fact, analysis by BNEF notes that green hydrogen has temporarily become cheaper than gray hydrogen in several large regions—Europe, the Middle East, Africa, and China—with natural gas prices rising due to the war in Ukraine (Collins 2022). But as with industrial electrification, producing green hydrogen at scale will need even further increases in renewable electricity installed capacity (Taibi et al. 2020). Reaching 1.5°C-aligned green hydrogen production targets, for example, will require installed renewable energy capacity to reach about 1–2 TW by 2030 and 4–8 TW by 2050.[29] The average size of planned electrolyzer plants is increasing steadily (currently projected to reach 230 MW in 2030 from a total of 0.6 MW in 2020), while several planned projects are in the GW scale. This is likely to reduce the cost of electrolyzers through achieving economies of scale (IEA 2021e). Reducing the cost of electrolysis facilities will also require investments in the research and development of innovations that improve the efficiency and the standardization and mass manufacturing of electrolyzers.

Investments in the R&D of low-carbon technologies for industry, however, remain concentrated primarily in high-income countries, while most of the growth in demand and consequent increased production of industrial products is expected to occur in low- and middle-income countries. Given the long lifetimes of industrial technologies and infrastructure (e.g., emissions-intensive blast furnaces can last 20–40 years), there is a high risk of carbon lock-in across industries in developing countries should they not have access to low-carbon innovations. Investments in the form of concessional financing by multilateral development banks, development finance institutions, and donor countries are essential to significantly reduce the costs of new technologies and innovations and enable their uptake by developing countries. The window of opportunity to channel investments into low-carbon industry and away from carbon-reliant infrastructure and technology with long lifetimes is now.

Set green hydrogen targets

Governments setting green hydrogen production and consumption targets send clear, long-term signals to the private sector. Green hydrogen consumption targets and demand-creation policies, such as minimum quotas for green hydrogen use in steel production, can increase confidence to invest in green hydrogen production as product offtake is ensured. Moreover, targets beyond production, such as setting aspirational targets for green hydrogen pricing, can also be helpful.

Even though there is growing political interest in, as well as private sector support for, green hydrogen, existing national and regional pledges would result in an installed electrolyzer capacity of 75 GW by 2030—far short of the 850 GW of installed capacity required in 2030 (IEA 2021e). However, additional efforts are expected to be announced in the short term, as governments are developing strategies and roadmaps that often include targets to stimulate demand, incentivize production, and develop infrastructure (e.g., promoting hydrogen hubs with facilities for hydrogen production and utilization). As of 2019, only Japan and Korea had published hydrogen strategies, but by 2021, 26 countries—including Australia, Canada, Chile, Germany, and Russia—had done so. While China doesn't have a national policy yet, over a third of its provinces have formulated hydrogen strategies on their own (Yuki 2021). BNEF estimates that another 22 countries will publish strategies in 2022 (BNEF 2022b). Beyond targets, policies need to adopt effective regulatory controls and standards to address potential leakage (Fan et al. 2022). Ultimately, governments' interest in hydrogen is likely to catalyze private sector investments across the value chain, as businesses anticipate favorable policies and financial support (Griffiths et al. 2021; Radowitz 2021). For example, several investment platforms focused on advancing green hydrogen production were established by private businesses and investment institutions in the United States, India, and Europe in 2021, signaling an uptick in private sector engagement (Defiance ETFs 2022), and at least four green hydrogen companies are planning to go public this year (BNEF 2022b).

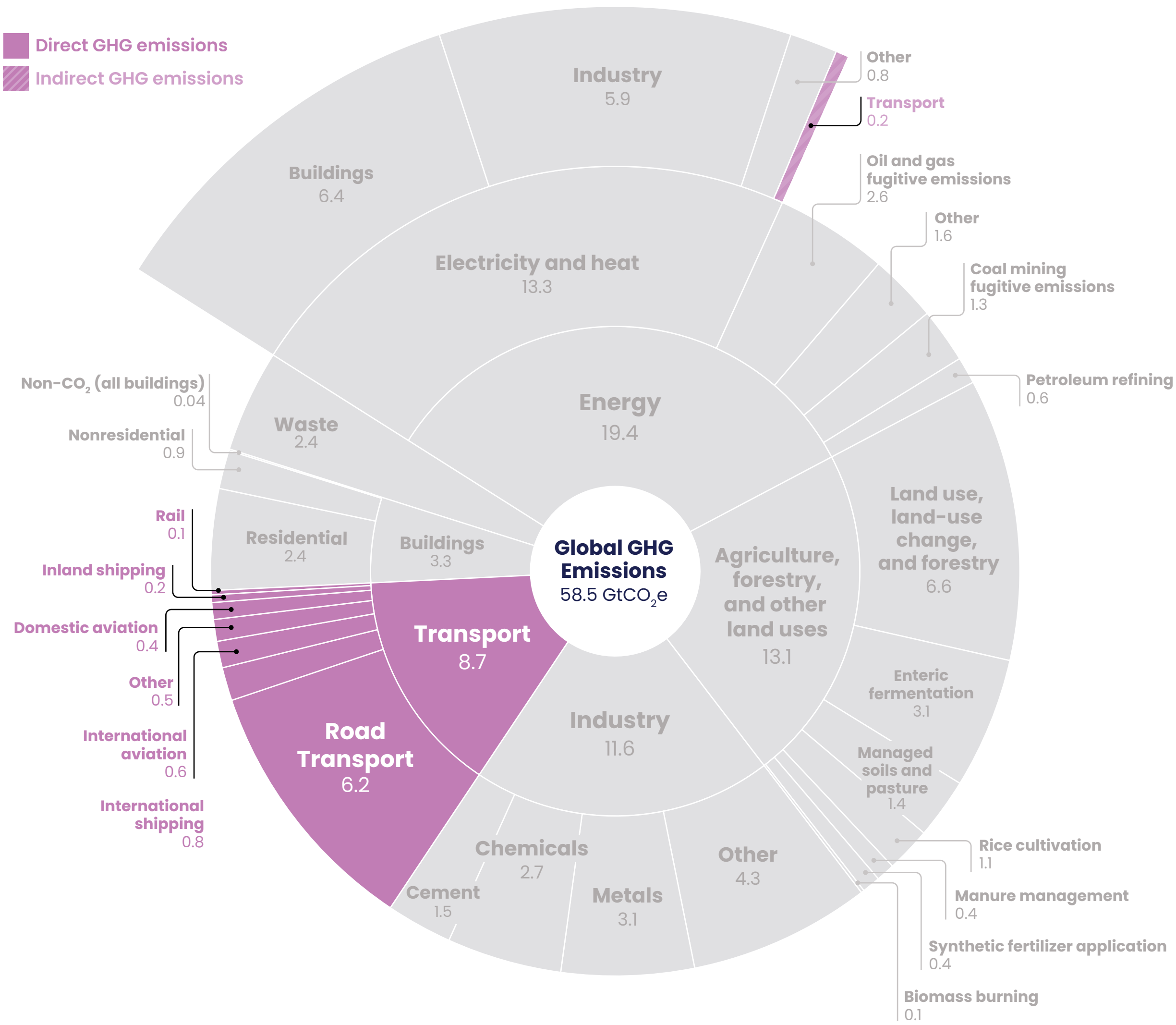
SECTION 5

Transport

Transportation networks connect people to one another, as well as to everything they need to live fulfilling lives: education, jobs, goods, and services. However, current transport systems are not accessible to all and contribute significant carbon pollution to the atmosphere. Since 1990, for example, increased car ownership and travel due to economic development has driven steady increases in GHG emissions from transport (IEA 2020e) with systemwide emissions reaching approximately 8.7 $GtCO_2e$ in 2019 before dropping to 7.6 $GtCO_2e$ in 2020 during the COVID pandemic (Figures 28 and 29) (Minx et al. 2021). An estimated 72 percent of transportation emissions in 2020 came from road vehicles, followed by 12 percent from maritime shipping, 9 percent from aviation, and 7 percent from rail and other sources (Figure 29). In 2021, transport emissions began to rise again, recovering about 44 percent of the decrease in CO_2 emissions from 2019 to 2020 (IEA 2022c).

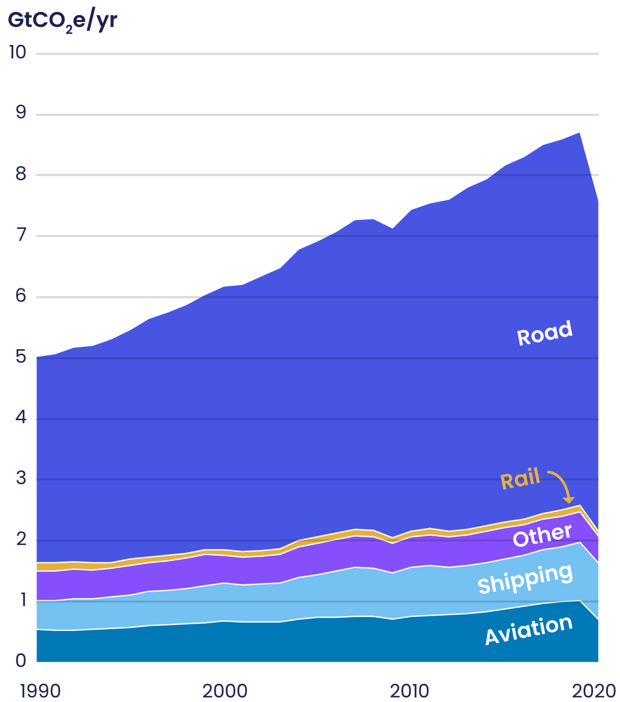
Transforming the global transportation system to reverse this trend will require three key shifts tracked in this report. First, travel must shift to or remain as active modes (including walking and bicycling) and shared public transport. For this shift, this report tracks short- and medium-distance mode shift via the share of kilometers traveled by passenger cars, the kilometers of urban rapid transit per 1 million inhabitants, and the kilometers of high-quality, safe urban bike lanes per 1,000 inhabitants. Long-distance mode shift is not accounted for in this report due to data limitations and space constraints. Second, governments must phase out the internal combustion engine and move to zero-carbon road vehicles. Finally, the shipping and aviation systems must decarbonize through a combination of demand-reduction strategies and zero-carbon technologies. For these shifts, this report tracks the share of electric vehicles (EVs) in annual light-duty vehicle

FIGURE 28 | Transport's contribution to global GHG emissions in 2019



Notes: CO_2 = carbon dioxide; GHG = greenhouse gas; $GtCO_2e$ = gigatonnes of carbon dioxide equivalent.
Source: Minx et al. (2022), described in Minx et al. (2021) and used in IPCC (2022b).

FIGURE 29 | Global GHG emissions from transport



Notes: GHG = greenhouse gas; $GtCO_2e/yr$ = gigatonnes of carbon dioxide equivalent per year.
Source: Minx et al. (2022), described in Minx et al. (2021) and used in IPCC (2022b).

sales, the share of EVs in the light-duty vehicle fleet, the share of zero-emission vehicles (ZEVs) in annual bus sales, the share of ZEVs in medium- and heavy-duty vehicle sales, the share of sustainable aviation fuels in the aviation fuel supply, and the share of zero-emission fuels in the maritime shipping fuel supply (Table 6).

Another key shift in the transportation system is to reduce car dependency and distances traveled (especially by car and by plane), especially in high-income regions where car dependency is high. This should not necessarily be a standard applied to all regions, however—access to mobility must be increased in areas where it is low, and in some cases vehicle travel is the only option when active modes or public transit are not feasible. Reducing car dependency and distance traveled requires a combination of more multimodal planning, transportation demand-management policies that encourage travelers to use the most efficient option for each trip, and smart growth development policies that create more compact communities where it is easy to get around without driving. This shift is out of the scope of this report due to space constraints and data limitations, but it will be accounted for in future Systems Change Lab products.

TABLE 6 | Summary of global progress toward transport targets

INDICATOR	MOST RECENT DATA POINT (YEAR)	2030 TARGET	2050 TARGET	TRAJECTORY OF CHANGE	ACCELERATION FACTOR	STATUS
Share of kilometers traveled by passenger cars (%)	44 (2020)	34–44	N/A		N/A; U-turn needed[a]	
Number of kilometers of rapid transit (metro, light-rail, and bus rapid transit) per 1 million inhabitants (in the top 50 emitting cities) (km/1M inhabitants)	19 (2020)	38	N/A		6x[a]	
Number of kilometers of high-quality bike lanes per 1,000 inhabitants (in the top 50 emitting cities) (km/1,000 inhabitants)	0.0077 (2020)	2	N/A		>10x[a]	
Carbon intensity of land-based passenger transport (gCO_2/pkm)	100 (2014)	35–60	0		Insufficient data	
Share of electric vehicles in light-duty vehicle sales (%)	8.7 (2021)[b]	75–95	100 (2035)		5x	[c]
Share of electric vehicles in the light-duty vehicle fleet (%)	1.3 (2021)[b]	20–40	85–100		>10x	
Share of battery electric vehicles and fuel cell electric vehicles in bus sales (%)	44 (2021)[b]	60	100		>10x[d]	[c]
Share of battery electric vehicles and fuel cell electric vehicles in medium- and heavy-duty vehicle sales (%)	0.2 (2021)[b]	30	99		Insufficient data	[c]
Share of sustainable aviation fuels in global aviation fuel supply (%)	0.03 (2020)	13–18	78–100		Insufficient data	[c]
Share of zero-emission fuels in maritime shipping fuel supply (%)	0 (2018)	5–17	84–93		Insufficient data	[c]

Notes: gCO_2/pkm = grams of carbon dioxide per passenger kilometer; km/1M inhabitants = kilometers per one million inhabitants; km/1,000 inhabitants = kilometers per one thousand inhabitants.

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

[b] Data for these indicators are not publicly available and were accessed with paid licenses to datasets or with permission from the data provider.

[c] The category of progress was adjusted for indicators categorized as exponential change likely, using methods outlined in this report's companion technical note (Schumer et al. 2022), and so in these instances, the category of progress identified does not always match the acceleration factor calculated using a linear trendline.

[d] We adjusted this indicator's category of progress, using methods outlined in Schumer et al. (2022). Historically, the share of battery electric vehicles and fuel cell electric vehicles in bus sales globally has been highly dependent on the adoption of electric buses in China. But from 2018 to 2020, sales in China dipped, in part, due to changing subsidies and because the share of electric buses in many Chinese cities' fleets is fast approaching 100 percent (BNEF 2021b). From 2017 to 2021, the average annual rate of change in sales share was -0.1 percentage points, suggesting that recent rates of change are heading in the wrong direction entirely. However, the sales share picked back up from 2020 to 2021, surpassing their previous peak. And when accounting for the longer-term trend, it is clear that the change in this indicator is not going in the wrong direction. Therefore, we set the acceleration factor as >10x and categorize this indicator as off track.

Sources: Historical data from ITF (2021), ITDP (2021), OpenStreetMap Foundation (n.d.), IEA (2017), BNEF (2022a), Air Transport Action Group (2021), and IMO (2020); targets from Climate Action Tracker (2020b), IEA (2021j, 2021k), Mission Possible Partnership (2022a), UMAS (2021), and BNEF (2021b).

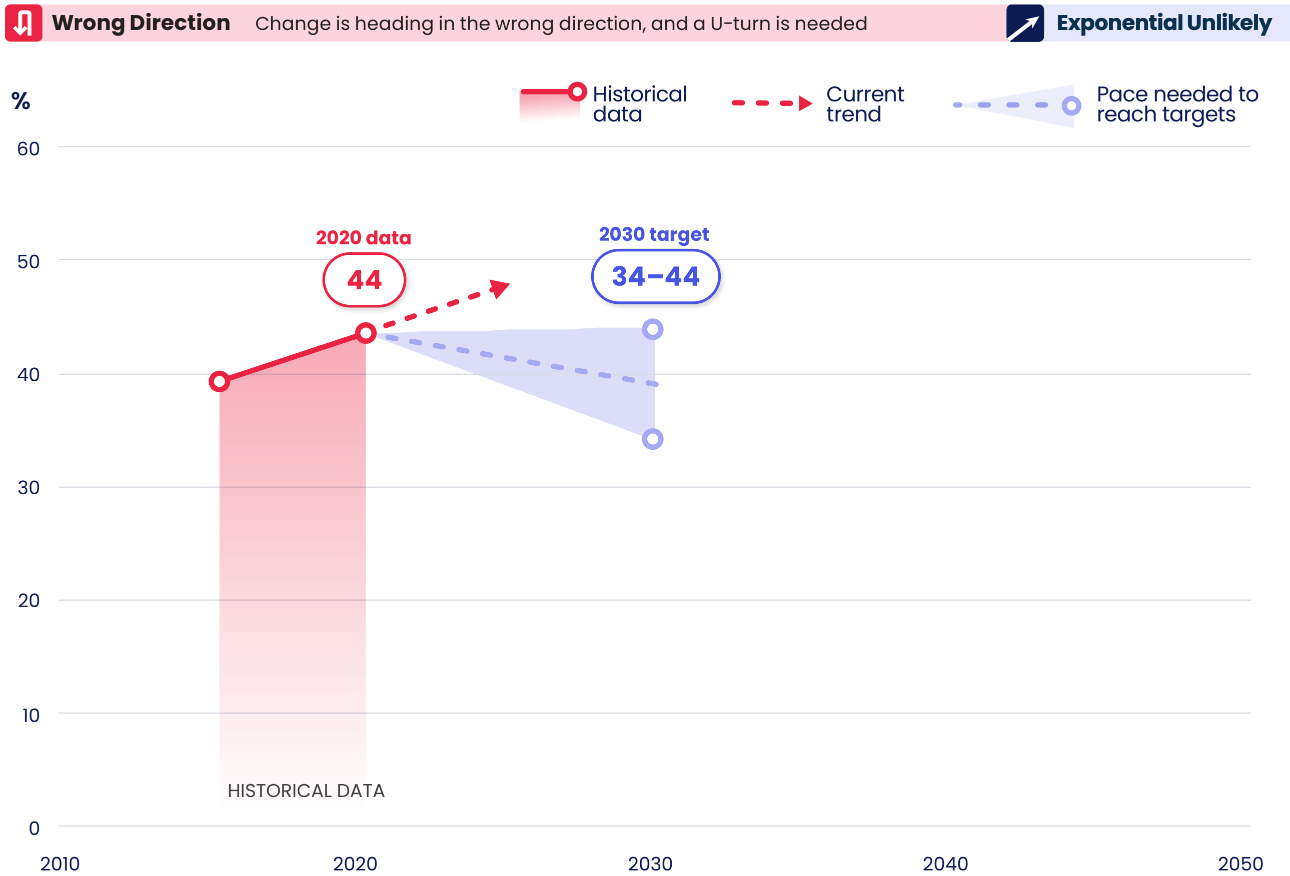
Status of transport indicators

TRANSPORT INDICATOR 1: Share of kilometers traveled by passenger cars (%)

- **Target**: People around the world reduce the percentage of trips made in passenger cars by 4–14 percent by 2030, relative to business-as-usual levels.

While extensive historical data are not available on the share of trips made by passenger cars, the data that do exist show a worrying trend. The share of trips made by passenger cars increased from 39 percent in 2015 to 44 percent in 2020 (Figure 30) (ITF 2021). The cause of this increase is understandable: as population and gross domestic product (GDP) have grown, so have the number of people who own cars, and therefore the share of trips made by privately owned cars (World Bank 2014). The trend in car ownership is expected to be exacerbated mostly from increases in developing countries as GDP continues to grow. Countries with the highest GDP per capita have therefore been responsible for the current state of this indicator, while countries with lower GDP per capita bear less of a responsibility. 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).

FIGURE 30 | Historical progress toward 2030 target for share of kilometers traveled by passenger cars



Notes: Due to data limitations, an acceleration factor is calculated for this indicator using methods from Boehm et al. (2021).

Sources: Historical data from ITF (2021); 2030 target derived from authors' analysis; calculations for projections based on BNEF (2021b), accessed with permission from Bloomberg New Energy Finance.

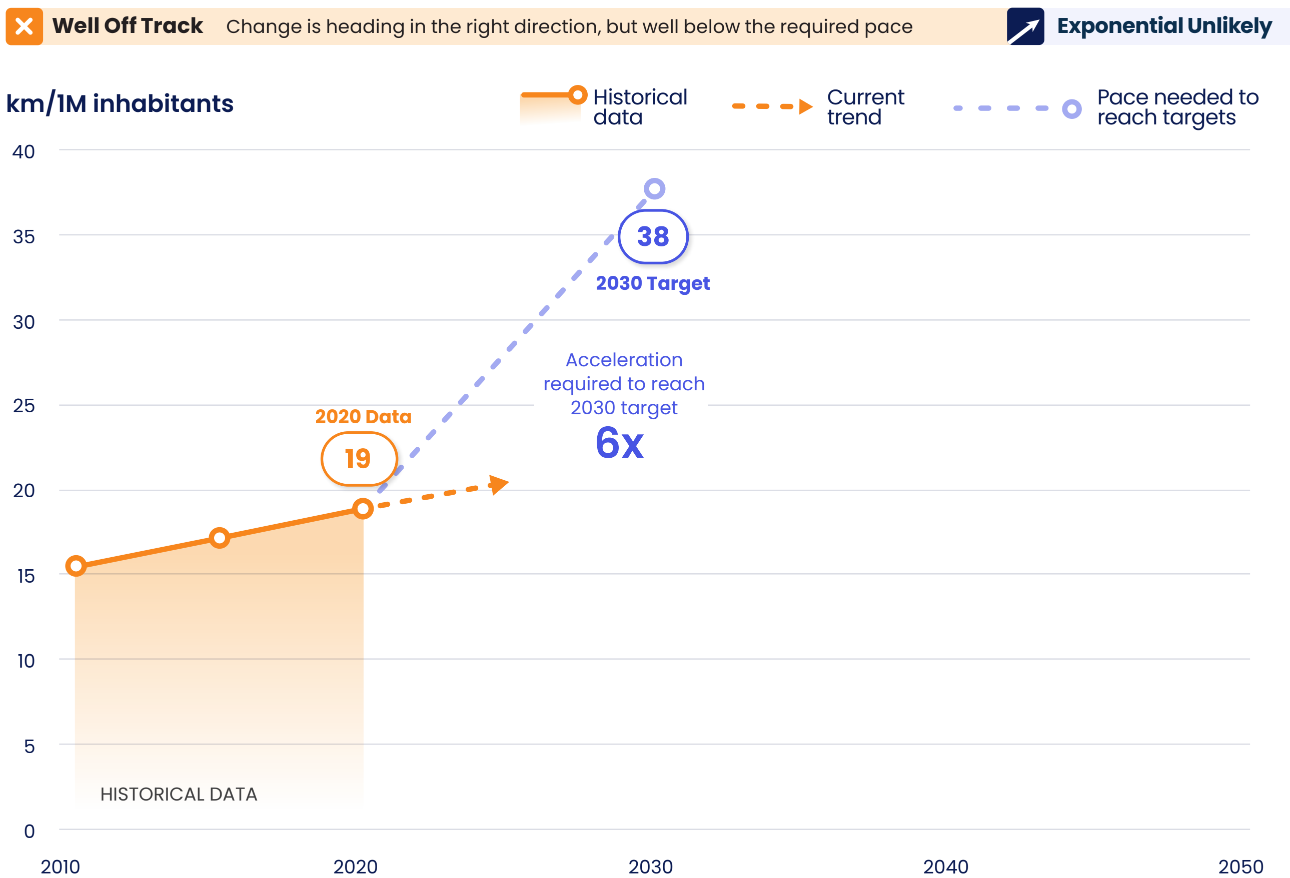
TRANSPORT INDICATOR 2:

Number of kilometers of rapid transit (metro, light-rail, and bus rapid transit) per 1 million inhabitants (in the top 50 emitting cities) (km/1M inhabitants)

- **Target**: Rapid transit infrastructure (metro, light-rail, and bus rapid transit), as measured in kilometers per 1 million inhabitants across the top 50 emitting cities, doubles by 2030, relative to 2021.

Buses and trains will be a crucial component of decarbonizing the transport sector as they can release as little as a fifth of emissions per passenger kilometer compared to ride-hailing and about a third of that of a private vehicle (ITF 2020). Today, more than half the world's population lives in cities, and that share is anticipated to grow to two-thirds by 2050 (UNDESA 2019). Across the 50 highest-emitting cities (Moran et al. 2018), the number of kilometers of rapid transit infrastructure per 1 million inhabitants has increased over time, from 16 in 2010 to 19 in 2020 (Figure 31). As the urban population grows, investment in rapid transit in cities and their metro regions tends to grow so that inhabitants can move easily and access opportunities (Mahendra et al. 2021; Coalition for Urban Transitions 2019). Likewise, in many dense cities, the number of lanes allocated for private vehicles has been decreased in favor of bus only, bike, and high-occupancy vehicle lanes. 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).

FIGURE 31 | Historical progress toward 2030 target for number of kilometers of rapid transit (metro, light-rail, and bus rapid transit) per 1 million inhabitants (in the top 50 emitting cities)



Notes: km/1M inhabitants = kilometers per 1 million inhabitants. Due to data limitations, an acceleration factor is calculated for this indicator using methods from Boehm et al. (2021).

Sources: Historical data from ITDP (2021) and authors' analysis.

TRANSPORT INDICATOR 3:

Number of kilometers of high-quality bike lanes per 1,000 inhabitants (in the top 50 emitting cities) (km/1,000 inhabitants)

- **Target**: Urban areas in the top 50 emitting cities contain two kilometers of high-quality, safe bike lanes per 1,000 inhabitants by 2030.

In 2020, there were approximately 0.0077 kilometers of segregated bike lanes per 1,000 inhabitants in the top 50 emitting cities, which will need to increase more than 10-fold by 2030 to be on a 1.5°C pathway (Figure 32). Bike use surged during the COVID-19 pandemic, and countries and cities should capitalize on that interest and prioritize cycling, the mode of transportation with the lowest carbon emissions after walking (Bernhard 2020; Yildiran 2022). European countries like Denmark, the Netherlands, and Germany lead in creating safe, convenient, and accessible cycling conditions, while cities like Paris are setting bold aspirations for cyclability (Pucher and Buehler 2008; City of Paris 2021). In addition, recent

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

Note: km/1M inhabitants = kilometers per 1 million inhabitants. Due to data limitations, an acceleration factor is calculated for this indicator using methods from Boehm et al. (2021).

Sources: Historical data from authors' analysis using OpenStreetMap Foundation (n.d.); see Schumer et al. (2022) for details.

cost reductions in electric bikes are making cycling more accessible for those in geographies with hot climates and steep hills.

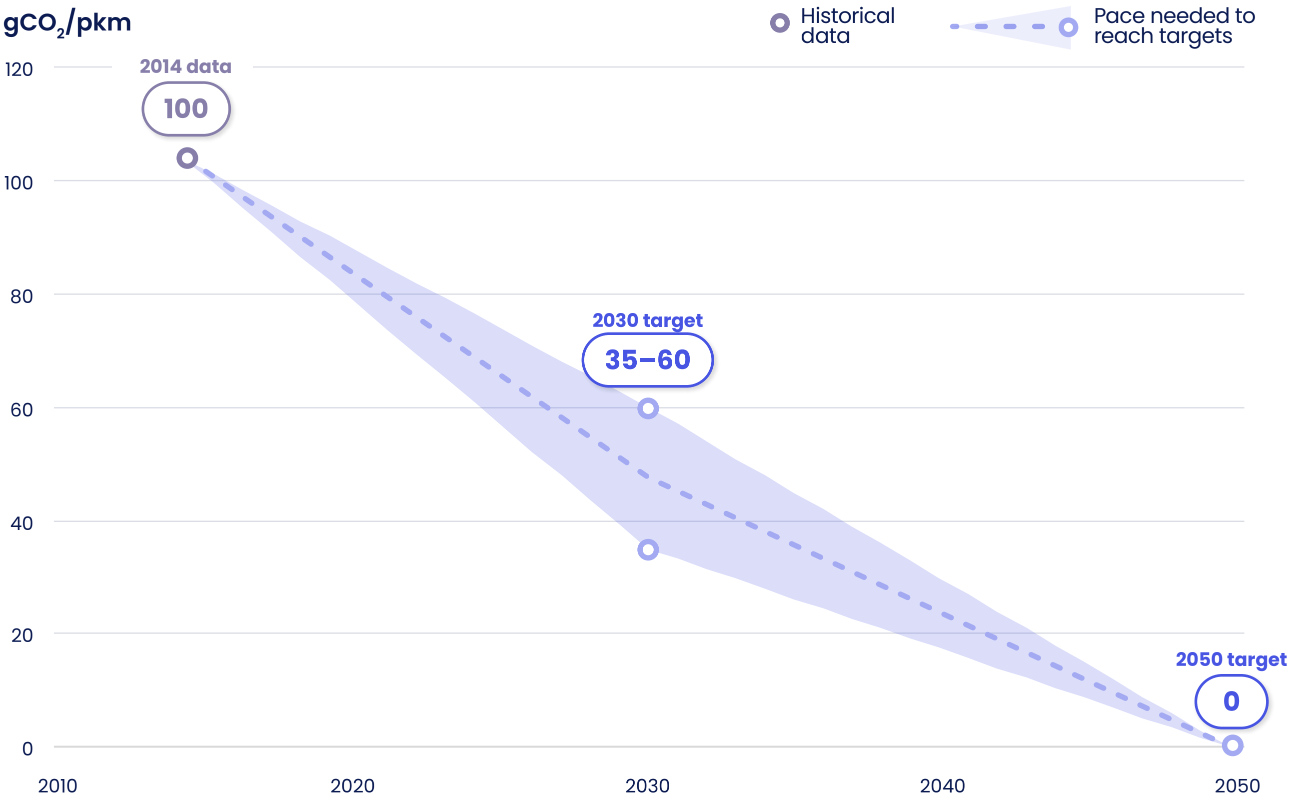
TRANSPORT INDICATOR 4: Carbon intensity of land-based passenger transport (gCO_2/pkm)

- **Target**: The carbon intensity of land-based passenger transport falls to 35–60 grams of carbon dioxide per passenger kilometer (gCO_2/pkm) by 2030 and reaches near zero by 2050.

In 2014, the only year of available data,[30] the carbon intensity of land-based passenger transport, which includes cars, buses, and trains, was 100 gCO_2/pkm, but this needs to roughly halve by 2030 (Figure 33). In 2019, the carbon intensity of private automobiles was 240 gCO_2/pkm, with private automobiles making up around 40 percent of total transport emissions in that year (IEA 2020e). Progress in increasing the fuel efficiency of private automobiles has slowed as the popularity of sport utility vehicles has skyrocketed—the share of sport utility vehicles in car

FIGURE 33 | Historical progress toward 2030 and 2050 targets for carbon intensity of land-based passenger transport

Insufficient Data Data are insufficient to assess the gap in action required for 2030 **Exponential Possible**



Note: gCO_2 /pkm = grams of carbon dioxide per passenger kilometer.
Sources: Historical data from IEA (2017); targets from Climate Action Tracker (2020b).

sales leaped from 17 percent in 2010 to 41 percent in 2019 (Carpenter 2021). Not enough historical data are available to assess a trend for this indicator.

TRANSPORT INDICATOR 5:

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

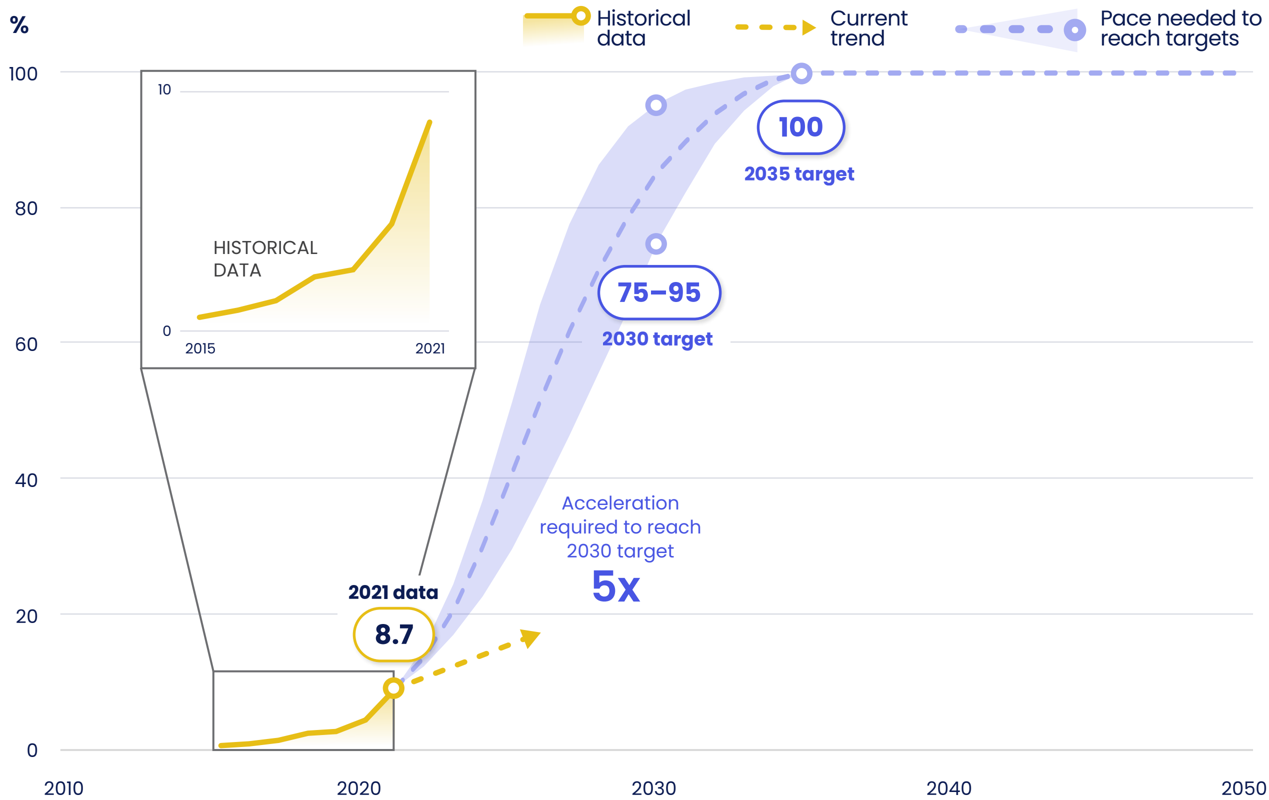
- **Target**: Electric vehicles (EVs) account for 75–95 percent of the total annual light-duty vehicle (LDV) sales by 2030 and 100 percent by 2035.

The share of EVs in LDV sales has begun to take off recently, reaching 8.7 percent in 2021, a doubling from 2020 (Figure 34) (BNEF 2022a). This represents about 6.6 million electric cars globally. Assuming linear growth, the rate of progress in EV car sales needs to be five times faster than it has been the past five years to reach 75–95 percent by 2030. However, EV deployment is likely to follow an S-curve and the technology is in the breakthrough stage of adoption, so the rate of change will likely go faster in the future compared to the past five years. Indeed, an acceleration already seems to be occurring. Based on purely linear growth this indicator would be well off track, but given the likelihood of exponential growth and our assessment of the literature, we upgrade the category to "off track." Bloomberg New Energy Finance expects global battery electric vehicles (BEVs) to reach 36 percent of light-duty vehicle sales in 2030, plus an additional 5 percent for plug-in hybrid EVs (BNEF 2022a).

The share of EVs in total car sales in China soared from 5 percent in 2020 to 16 percent in 2021, while Europe saw huge growth, from 3 percent in 2019 to 10 percent in 2020 and 17 percent in 2021, and U.S. sales hit 2 percent in 2019 and 2020 and just under 5 percent in 2021 (IEA 2022b). Rising sales in Europe and the United States are being driven primarily by a select number of countries and states. The share of battery electric passenger car sales in 2021 in countries like Norway (86 percent), Sweden (45 percent), and the Netherlands (30 percent), and states like California (12 percent) and Washington (8 percent) are well above the regional averages and are a sign of transformational change (European

FIGURE 34 | Historical progress toward 2030 and 2050 targets for share of electric vehicles in light-duty vehicle sales

Off Track Change is heading in the right direction at a promising but insufficient pace **Exponential Likely**



Note: The category of progress was adjusted for this indicator, which we categorized as exponential change likely, using methods outlined in Schumer et al. (2022). So in this instance, the category of progress identified does not match the acceleration factor calculated using a linear trendline.

Sources: Historical data from BNEF (2022a), accessed with permission from Bloomberg New Energy Finance; targets from Climate Action Tracker (2020b).

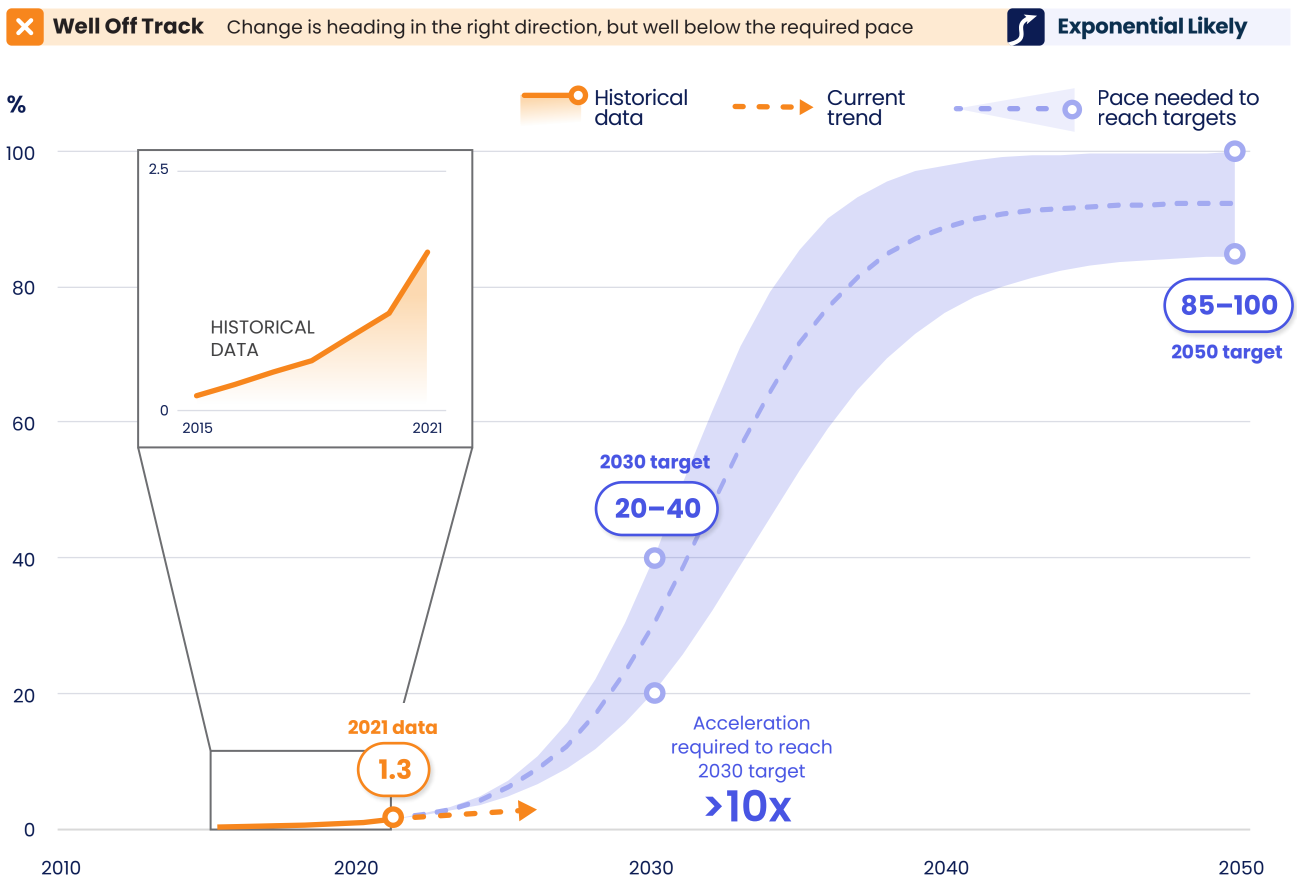
Alternative Fuels Observatory 2022; Ryan 2022; Office of Governor Newsom 2022). The rest of the world continues to register a low EV share of sales, but as prices continue to fall and model range grows further, this could change.

TRANSPORT INDICATOR 6:
Share of electric vehicles in the light-duty vehicle fleet (%)

- **Target**: EVs account for 20–40 percent of the total LDV fleet by 2030 and 85–100 percent by 2050.

The share of EVs in the global LDV fleet, an indicator that necessarily lags behind share of sales, reached 1.3 percent in 2021, an increase of over 60 percent from 2020 levels. (Figure 35). As the share of EVs in total global sales has only recently begun to rise considerably, a significant increase in their share of the total LDV fleet has yet to be seen, though it has increased by 25 times from very low levels since 2015. Assuming linear growth, the rate of progress in the EV light-duty fleet needs to be more than 10 times faster to reach 20–40 percent by 2030. However, because EV deployment is likely to follow an S-curve and the technology is in the breakthrough stage of adoption, the rate of change will likely go faster in the future compared to the past five years. This indicator is well off track but could increase exponentially as EV sales increase exponentially (Grubb 2021a; BNEF 2021b). Rapidly increasing sales volumes in the key markets of China, the European Union, and now the United States, lead to greater overall EV numbers, with total EV numbers in these three major markets combined rising from 1.9 million in 2016 to 9.4 million by 2020 (IEA 2021o). By the end of 2022, an estimated total of 26 million plug-in vehicles will be on the road, a staggering increase from just 1 million in 2016 (McKerracher 2022). Half of these are estimated to be in China.

FIGURE 35 | Historical progress toward 2030 and 2050 targets for share of electric vehicles in the light-duty vehicle fleet



Sources: Historical data from BNEF (2022a), accessed with permission from Bloomberg New Energy Finance; targets from Climate Action Tracker (2020b).

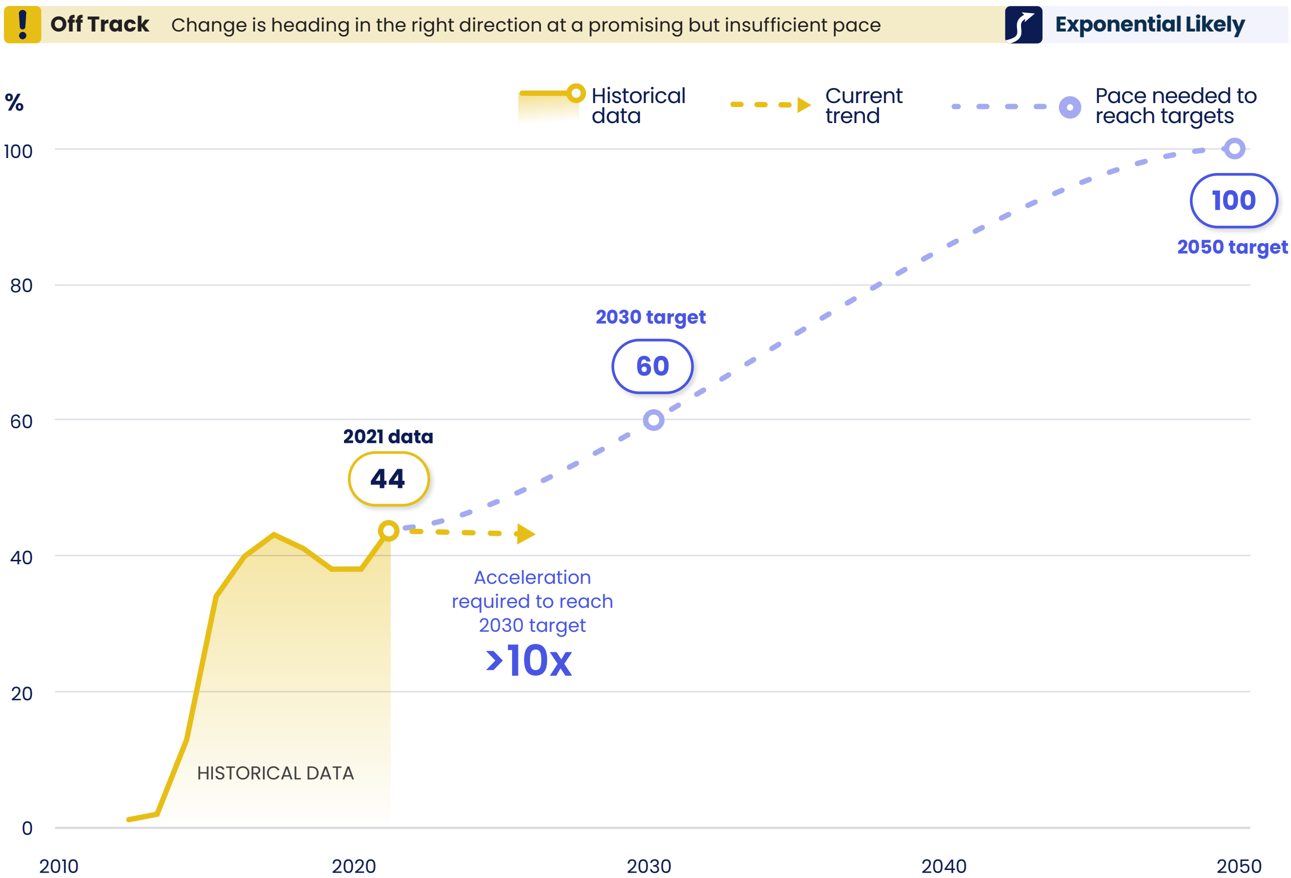
TRANSPORT INDICATOR 7:

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

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

The global share of zero-carbon bus[31] sales, reaching 44 percent in 2021, has been driven steeply higher since 2013, when they made up just 2 percent of sales, due almost entirely to Chinese demand, which made up 97 percent of sales in 2019 (Figure 36) (BNEF 2021b). Total sales rocketed from fewer than 5,000 in 2013 to over 100,000 per year in 2017 (43 percent share of total sales) before falling in 2018–19, though the total global fleet still 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). Because of recent fluctuations in sales shares, the rate of progress made in increasing the share of BEVs and FCEVs in bus sales needs to be more than 10 times faster than it has been the last five years to reach 60 percent by 2030. However, China has proved that rapid progress is possible for zero-carbon buses and has singlehandedly brought the 2030 target within reach. Other countries have the potential for that same exponential progress (BNEF 2021b). Therefore, we have chosen to upgrade the indicator from well off track, where it would be based purely on the last five years, to off track.

FIGURE 36 | Historical progress toward 2030 and 2050 targets for share of battery electric vehicles and fuel cell electric vehicles in bus sales



Note: The category of progress was adjusted for this indicator, which we categorized as exponential change likely, using methods outlined in Schumer et al. (2022). So in this instance, the category of progress identified does not match the acceleration factor calculated using a linear trendline. More specifically, the global share of battery electric vehicles and fuel cell electric vehicles in bus sales historically has been highly dependent on the adoption of electric buses in China. But from 2018 to 2020, sales in China dipped, in part, due to changing subsidies and because the share of electric buses in many Chinese cities' fleets is fast approaching 100 percent (BNEF 2021b). From 2017 to 2021, the average annual rate of change in sales share was -0.1 percentage points, suggesting that recent rates of change are heading in the wrong direction entirely. However, the sales share picked back up from 2020 to 2021, surpassing their previous peak. And when accounting for the longer-term trend, it is clear that the change in this indicator is not going in the wrong direction. Therefore, we set the acceleration factor as >10x and categorize this indicator as off track.

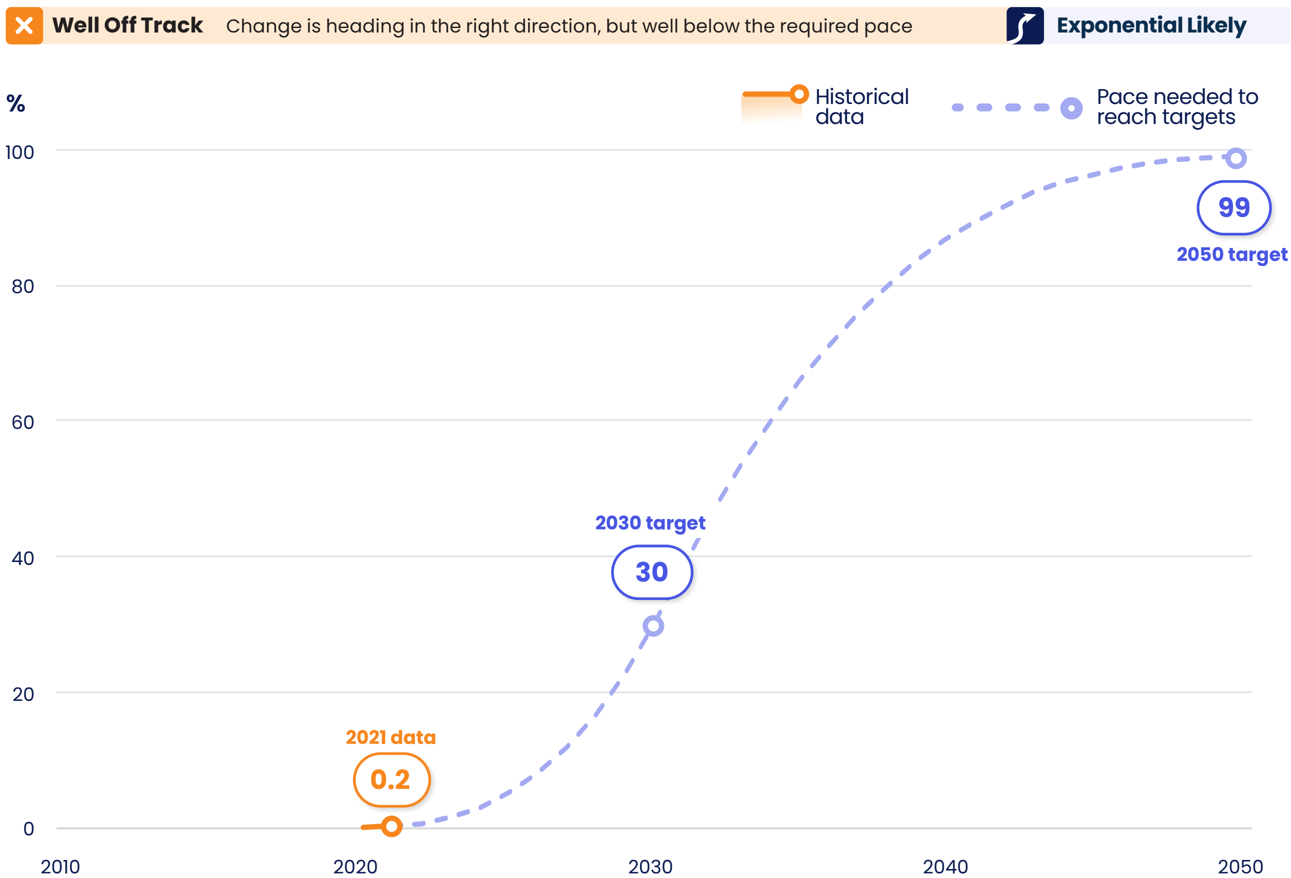
Sources: Historical data from BNEF (2022a), accessed with permission from Bloomberg New Energy Finance; targets from IEA (2021h).

TRANSPORT INDICATOR 8:
Share of battery electric vehicles and fuel cell electric vehicles in medium- and heavy-duty vehicle sales (%)

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

Global sales of zero-carbon MHDVs remain low, reaching roughly 0.2 percent of total sales in 2021 (Figure 37) (BNEF 2022a). As with buses, the bulk of global demand came from China, which accounted for 60 percent of total sales. Europe accounted for 23 percent of sales. This indicator is going in the right direction but well off track, as zero-carbon MHDV sales have only just begun to accelerate outside of China (IEA 2022b). Historical data are insufficient to establish how much recent zero-carbon MHDV sales would need to accelerate to reach 30 percent in 2030. Because zero-carbon MHDV deployment is a type of innovative technology adoption that often follows an S-curve and the technology is in the emergence stage of adoption, the rate of change will likely go faster in the future compared to the two years for which we have available data, although this is not guaranteed. With strong support from governments and collaboration across the value chain, we could see sales begin to increase exponentially given increasing model availability and the signs of exponential growth in other EV classes and across various countries and regions (BNEF 2021b; IEA 2022b).

FIGURE 37 | Historical progress toward 2030 and 2050 targets for share of battery electric vehicles and fuel cell electric vehicles in medium- and heavy-duty vehicle sales



Note: Bloomberg New Energy Finance has revised its historical sales share figures from the previous version of the *Electric Vehicle Outlook*, so this information is not comparable with that in *State of Climate Action 2021*. Also, although this indicator only has two data points, because it is new technology that could likely experience exponential change in the future, it is categorized as well off track, rather than insufficient data.
Sources: Historical data from BNEF (2022a), accessed with permission from Bloomberg New Energy Finance; targets from IEA (2021h).

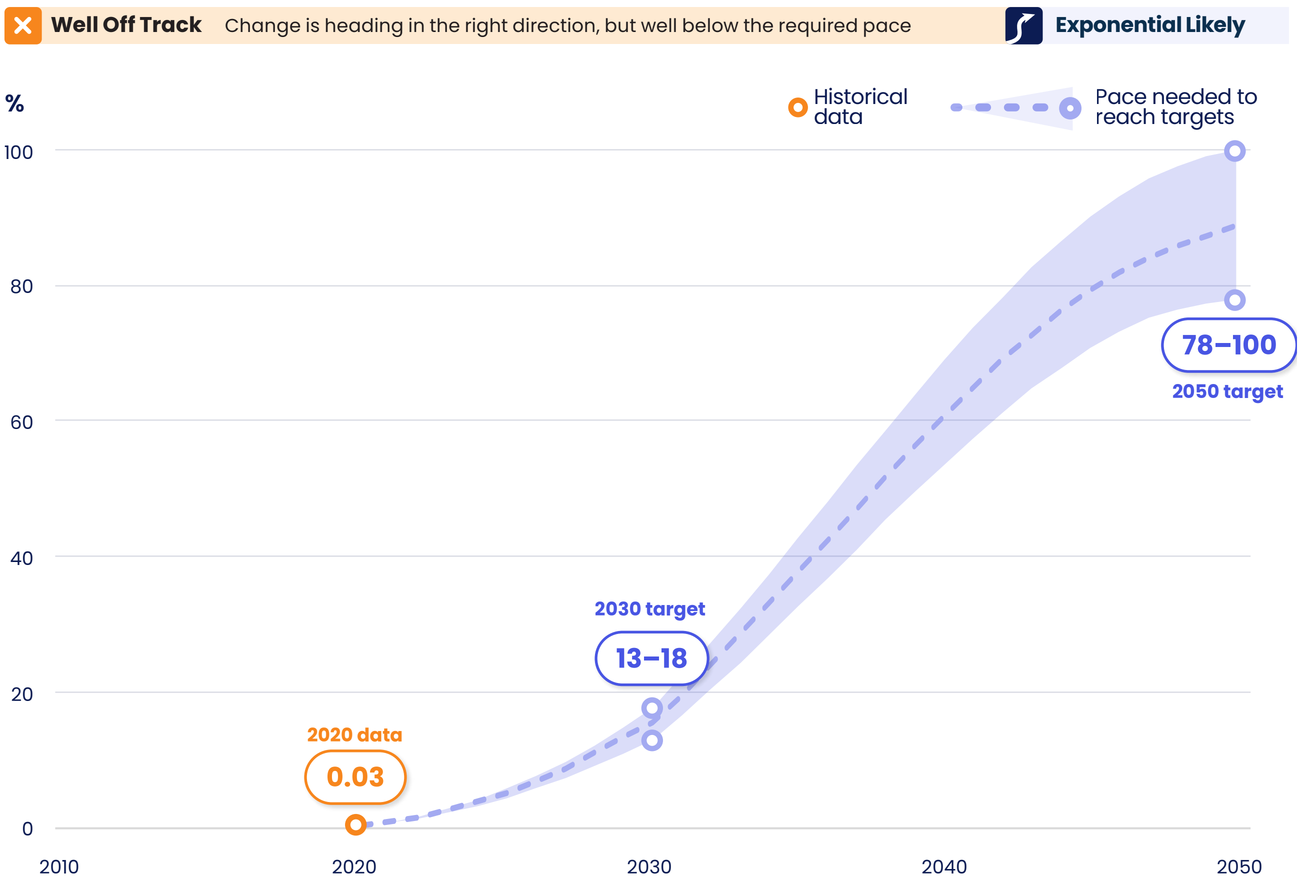
TRANSPORT INDICATOR 9:

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

- **Target:** Sustainable aviation fuels (SAFs) comprise 13-18 percent of global aviation fuel supply by 2030 and 78-100 percent by 2050.

The share of SAFs, including fuels made from biomass, alcohol, or electricity, in the global aviation fuel supply was less than 0.1 percent in 2020, the only historical data point currently available (Figure 38). Additionally, if overall jet fuel demand grows with expected passenger growth in the coming decades, the absolute amount of SAFs produced must increase just to maintain share levels (IEA 2021a). Historical data are insufficient to establish how much the rate of change would need to accelerate for the share of SAF to reach 13–18 percent in 2030. There are signs of SAF supply and use beginning to grow—airlines have secured purchase agreements for 21 million tonnes of SAFs, with delivery timelines ranging from 6 months to 20 years (Mission Possible Partnership 2022a). About 70 percent of the 21 million tonnes were agreed to in 2021 or 2022. Additionally, companies with large aviation footprints are working with airlines to purchase SAFs (see, e.g., Deloitte n.d. and *PR Newswire* 2022). Given the low levels of SAF use but the signs of progress, we have categorized this indicator as going in the right direction but well off track. SAF deployment is a type of technology adoption process that often follows an S-curve, and the technology is in the emergence stage of adoption. If we begin to see more promising developments pick up, in addition to blending mandates like the European Union's ReFuel EU proposal (see "Enabling conditions for climate action across transport" below), the share of SAFs in the global aviation fuel supply could begin to increase exponentially (WEF 2020; ETC 2019b; Race to Zero 2021a; BNEF 2021c).

FIGURE 38 | Historical progress toward 2030 and 2050 targets for share of sustainable aviation fuels in global aviation fuel supply



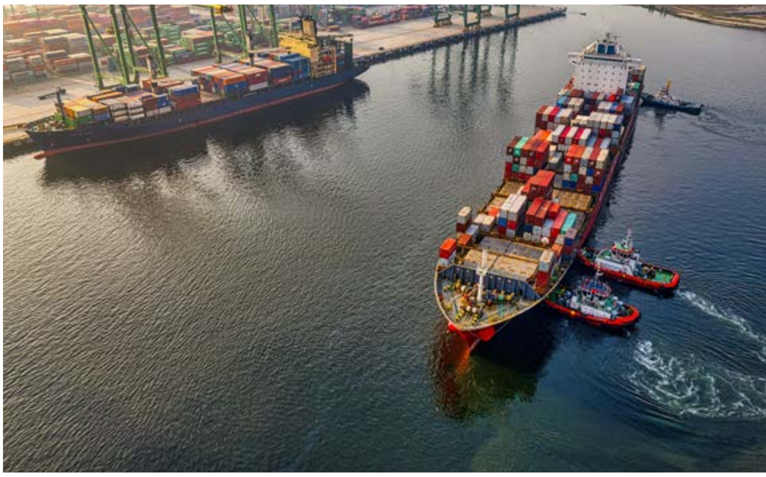
Note: Although this indicator only has one data point, because it is new technology that could likely experience exponential change in the future, it is categorized as well off track, rather than insufficient data.

Sources: Historical data from Air Transport Action Group (2021); targets from IEA (2021h) and Mission Possible Partnership (2022a).

TRANSPORT INDICATOR 10:

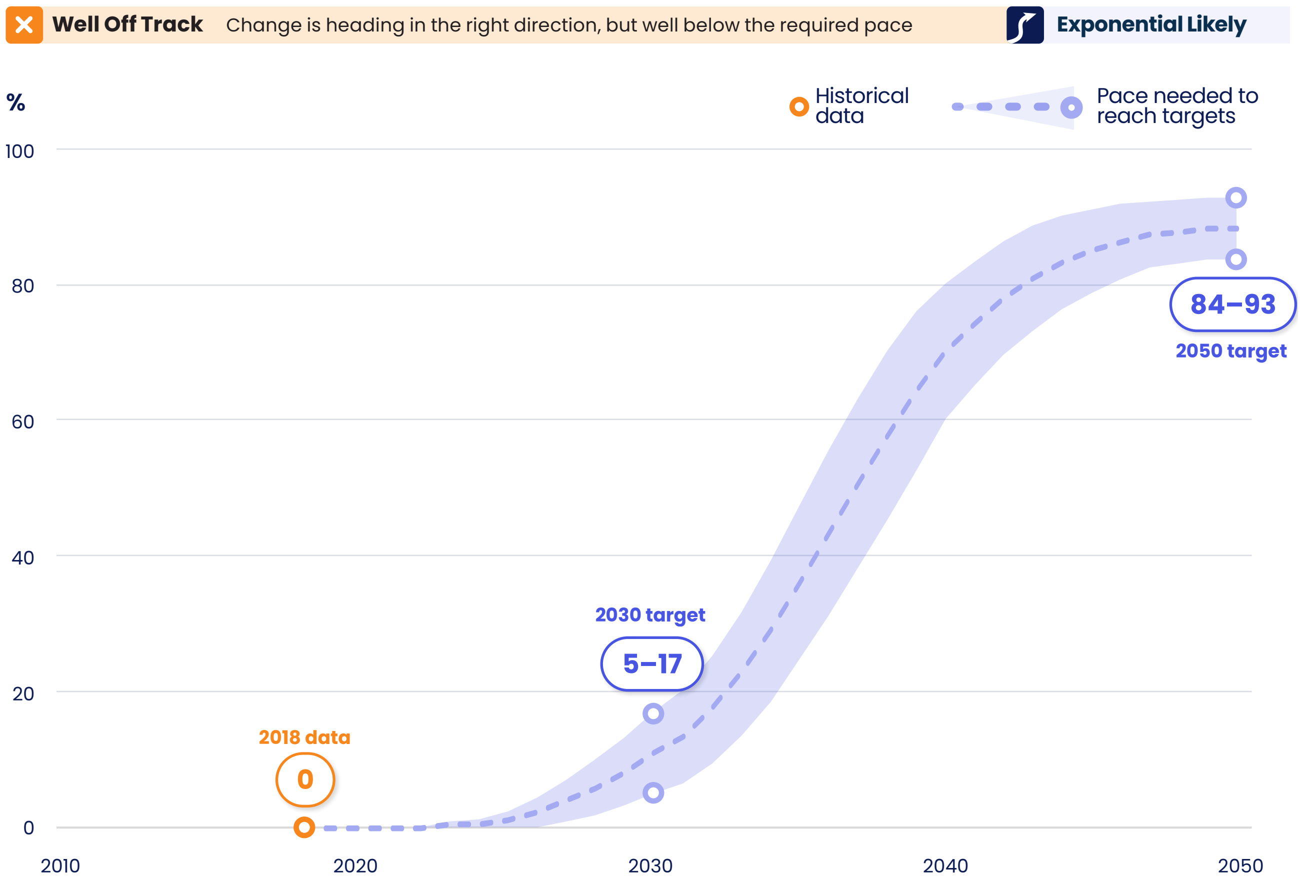
Share of zero-emission fuels in maritime shipping fuel supply (%)

- **Target**: The share of zero-emission fuels (ZEFs) in maritime shipping fuel supply reaches 5-17 percent by 2030 and 84-93 percent by 2050.



ZEFs for shipping include synthetic carbon-based fuels made from green hydrogen and captured CO_2 (e.g., e-methanol), as well as direct use of green hydrogen and ammonia.[32] ZEFs have not yet entered the maritime shipping fuel supply (Figure 39). Scenarios aligned with a 1.5°C pathway suggest that 5–17 percent of fuel used in maritime shipping will need to be zero-emission fuel by 2030 and 84–93 percent of fuel by 2050 (IEA 2021h; UMAS 2021). Because these fuels have not yet entered the market, there are no historical data to calculate how much faster growth will need to proceed for the share of ZEFs to reach 5–17 percent in 2030. However, because ZEF deployment is the type of technology adoption process that often follows an S-curve and the technology is in the emergence stage of adoption, the rate of change will likely be nonlinear in the future, although this is not guaranteed. However, there are over 200 pilot and demonstration projects to develop zero-emission shipping fuels as of the beginning of 2022 (Global Maritime Forum 2022). Given the lack of deployment but the signs of progress, we have categorized this indicator as going in the right direction but well off track.

FIGURE 39 | Historical progress toward 2030 and 2050 targets for share of zero-emission fuels in maritime shipping fuel supply



Note: Although this indicator only has one data point, because it is new technology that could likely experience exponential change in the future, it is categorized as well off track, rather than insufficient data.

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

Global assessment of progress for transport

Transportation emissions have increased significantly since 1990 (with a temporary dip in 2020), but pockets of progress are occurring that could reduce these emissions in the near to medium future.

Efforts to reduce travel demand by private modes have, unfortunately, been going in the wrong direction. This trend was exacerbated during the COVID-19 pandemic due to a preference for solo travel in private automobiles (Kim et al. 2021). Many jurisdictions continue to apply automobile-oriented transport planning that favors automobiles over other modes and encourages sprawl rather than compact development. More effort is needed to decouple economic growth from car use and ownership. Multimodal planning can help achieve economic, social, and environmental goals by favoring affordable and resource-efficient modes and creating communities where it is easy to get around without driving. Where these processes are implemented, they have been successful (see, e.g., Stapleton et al. 2017; Kuss and Nicholas 2022; Mehaffy et al. 2022; Spack and Finkelstein 2014; Eltis 2022; EPOMM n.d.; and ICLEI n.d.). These successes demonstrate the feasibility of significantly reducing vehicle travel under appropriate conditions, and the diverse benefits they provide, including infrastructure cost savings, consumer saving and affordability (savings to lower-income households), more independent mobility for nondrivers, improved public safety and health, and reduced sprawl costs. Additional investments in noncar infrastructure such as transit and high-quality bike lanes, coupled with policies such as transportation demand-management programs and compact zoning and development policies, are needed to achieve vehicle travel reduction targets.

The effort to switch from internal combustion engine (ICE) light-duty vehicles to electric vehicles has seen the clearest and most easily measurable progress in decarbonization. Sales of zero-emission vehicles have increased over the last six years for which we have data but are uneven across vehicle categories due to different needs in different categories. Sales of new passenger electric vehicles are growing the fastest, most recently seeing an increase of 67 percent from 2020 to 2021. Currently, they make up 8.7 percent of global passenger vehicle sales. While this seems low, it represents tremendous growth from 2015—an average of about a 50 percent increase per year (Dennis 2021). In addition, it is possible that as battery prices fall and EVs become as cheap as, or cheaper than, their ICE counterparts and governments implement appropriate policies (see “Enabling conditions for climate action across transport” below), EV sales may hit a tipping point and move beyond early adopters into even faster growth among mass market car buyers. Cars are not the only light-duty vehicles getting electrified—about 25 percent of the two-wheelers around the world are electric (particularly in China, where 95 percent of them are) (IEA 2021b). In 2020, e-bike sales in the United States grew 145 percent from the year before, and Europe in 2019 saw e-bike sales more than double those of battery electric or hybrid cars (Fleming 2021). One potential complicating factor in the growth of EV sales is that supply chain constraints have been emerging in 2021 and 2022. In 2022, three factors are driving supply chain disruptions: continuing production constraints from the COVID-19 pandemic, concerns about access to nickel from Russia (driven by its invasion of Ukraine), and the consequences of underinvestment in the supply of battery metals over the past four years (IEA 2022f). Additionally, the supply of vehicle components from factories in Ukraine has reportedly been disrupted due to

TABLE 7 | **Battery electric and diesel trucks total cost of ownership parity year under currently adopted policies**

	FRANCE	GERMANY	ITALY	NETHERLANDS	POLAND	SPAIN	UK
TCO parity without incentives	2025	2029	2028	2024	2027	2027	2026
TCO parity with adopted policies	2022	2021	2027	2022	2025	2026	2026

Note: TCO = total cost of ownership.
Source: Basma et al. (2021).

the Russian invasion (Hampel 2022). Constraints appear to be loosening, but this highlights the importance of supply chains to quick progress.

China, where almost 3 million EVs were sold in 2021, continues to be the biggest market for zero-emission passenger road vehicles (MIIT 2022). But the share of EVs in sales is highest in Europe, at just over 17 percent. While increasing the sale of EVs is important, the ultimate goal is to replace the ICE vehicles on the road with zero-emission counterparts and ensure that all new car sales are zero-emission. It is likely that the share of EVs on the road will continue to increase, as ICE vehicle sales peaked in 2017 and are shrinking while EV sales grow (BNEF 2022a).

After private automobiles, trucks and buses constitute the next-largest global CO_2 emissions source from the transport sector (2.2 $GtCO_2$ in 2020), more than aviation and shipping emissions combined (1.9 $GtCO_2$ in 2019, the last full year unaffected by the COVID-19 pandemic) (IEA 2021p). Over half of these 2.2 $GtCO_2$ emissions are from heavy-duty trucks alone, while buses make up just under a fifth. Progress on decarbonizing these forms of transport has been uneven over the last decade. Because vehicles like medium- and heavy-duty trucks and buses are typically managed in fleets rather than being purchased individually by private owners, it is possible that this segment could move more quickly than cars because fewer people are making decisions about more vehicles. China has made large strides in adopting electric buses, almost single-handedly raising the EV share of global bus sales from 2 percent in 2013 to 44 percent under a decade later (BNEF 2022a). In 2020, China made up 94 percent of total EV bus sales, with Europe the next-largest contributor, at 3 percent.

Meanwhile, zero-carbon medium- and heavy-duty commercial vehicles made up just 0.2 percent of global sales in 2021, an important metric that demonstrates the disappointing progress made on decarbonizing this form of transport. Recent analyses on total cost of ownership of battery electric MHDVs show that some BEV models are already less expensive to own and operate than their diesel equivalents in a number of countries when local adopted policies are considered, including purchase incentives, carbon pricing for transport, and road toll adjustments (Table 7) (Basma et al. 2021). This implies that demand will likely begin to rise if these policies remain in place or are strengthened. Notably, research has shown that fluctuating fossil fuel prices and electricity prices can affect the total cost of ownership and therefore when EVs will reach parity (Basma et al. 2022). While electric vehicles have dominated light-duty vehicle sales, medium- and heavy-duty vehicles are likely to see a broader technology mix of zero-emission vehicles that includes electric vehicles and hydrogen fuel cell vehicles (Xie et al. 2022).

Solutions for decarbonizing aviation and shipping are not as prevalent as those for road transport, but, as will be discussed below, these modes are receiving increasing global attention and new efforts to bring technologies to scale. At about 12 percent of total transport CO_2 emissions (about 1 $GtCO_2$), aviation is a small contributor compared to road transport, but emissions have been growing—left unchecked, they could increase to over 2 $GtCO_2$ by 2050 (Mission Possible Partnership 2022a). In addition, aviation contributes non-CO_2 greenhouse gases through the water vapor in contrails. In 2021, the International Civil Aviation Organization began implementing its Carbon Offsetting and Reduction Scheme for International Aviation to offset any aviation emissions above 2019 levels. By itself, this scheme will not be sufficient to ensure alignment with 1.5°C; it will need to be complemented with additional actions to reduce aviation emissions on an absolute basis (Climate Action Tracker 2022b). Also in 2021, the aviation industry agreed on a goal of reaching net-zero CO_2 emissions by 2050 (IEA 2021a). A key policy development is the ReFuel EU proposal in the European Union, which will require an increasing share of SAFs in fuel use, climbing from 2 percent in 2025 to 63 percent in 2050 (European Council 2022). This kind of policy mandate could be key in ensuring that SAF use increases in aviation. In addition to SAF development, key levers include reducing demand for air travel (including by shifting to other modes such as rail), aircraft efficiency improvements, and operational measures such as air traffic management and route planning (Mission Possible Partnership 2022a).

Shipping accounts for about 13 percent of total transport CO_2 emissions (just over 1 $GtCO_2$) and total GHG emissions closer to 1.1 $GtCO_2e$ (IMO 2020). The International Maritime Organization (IMO) has committed to at least halving GHG emissions from 2008 levels by 2050, an initial strategy that features short- and long-term measures including fuel efficiency controls as well as the use of alternative fuels (IEA 2021g). Momentum is building for a shipping goal of zero GHGs by 2050; this will need to be agreed upon by IMO members in 2023 (UMAS 2022b).

While measures to shift to lower carbon modes will play an important role in reducing transport emissions, a decarbonized transport system is going to be heavily linked with a decarbonized power system due to the role of electricity in EVs and in creating new fuels for shipping and aviation. Studies have shown that EVs have lower emissions than ICE vehicles with the current grid mix across major markets, and additional progress in cutting the carbon intensity of power generation will increase the CO_2 savings of EVs (Bieker 2021). Inasmuch as we can divert personal trips away from car trips, we in turn reduce demand on and for a new electric grid, as well as for lithium and other precious metals needed to produce batteries. If the production of green hydrogen increases sufficiently, it could play a significant role in the transport system, especially in shipping and aviation. Green hydrogen production in industry would then be intrinsically linked to the success of transport decarbonization. The built environment will also be important to decarbonizing transportation because charging infrastructure is integrated with urban planning and often part of buildings.

In high-income economies where new car purchases are high, there have been concerns about how accessible EVs are to lower income strata (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 (Muehlegger and Rapson 2019; Borenstein and Davis 2016). More recent analysis 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). However, because walking and bicycling are significantly less expensive than buying a new or used vehicle (ITDP 2022), there are arguments to be made that equity would be better served by investments in active transportation modes and making it easier to get around without a car than by microtargeting subsidies for electric cars.

Internationally, there is an inequity between developed countries, where new car sales are common, and developing countries, where used cars are frequently imported from developed countries. From 2015 to 2018, the European Union, Japan, and the United States exported 14 million used LDVs and 1.2 million used HDVs (UNEP 2020b). 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 dirty vehicles to developing countries, shifting the transition burden to them.

From a jobs perspective, the transition to EVs is complicated but important in the context of a just transition. EVs require fewer parts and less maintenance than ICE vehicles—according to German manufacturer Bosch, an electric drivetrain requires 10 times fewer workers to assemble than a diesel powertrain (Neslen 2021). There is evidence that electrification will drive some changes in areas of manufacturing—especially in components, fewer of which are required in an electric drivetrain than a conventional powertrain (Fraunhofer IAO 2020). However, looking at manufacturing and deployment as a whole provides a slightly different picture. One recent study estimates that plug-in hybrid manufacturing would drive a net increase of 43,000 auto sector jobs in Europe by 2030, but the sector would begin to lose jobs after 2035 while jobs would soar in electrical equipment and hydrogen for electric and hydrogen vehicles (Cambridge Econometrics and Element Energy 2018). Another estimates that new jobs in electricity infrastructure build-out and steady auto manufacturing employment would offset job losses in vehicle repair, leading to a net increase of about 300,000 new jobs in electricity and fuel supply in the United States by 2035 with a transition to EVs (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.

There are plenty of jobs to be created in other parts of the transport system, however, including building and maintaining transit and cycling infrastructure and building supply chains for new transport fuels. For example, every $1 million spent on pedestrian and bike lanes is estimated to produce 8–22 new jobs (IEA 2020d).

Enabling conditions for climate action across transport

Some progress is being made in most indicators tracked in this section, even if it is not as fast as is necessary for a 1.5°C scenario. Lawmakers around the world are still spending too little on public transport, walking, and cycling. Relatedly, many current transport and land-use development policies favor automobile travel over more affordable and resource-efficient modes, and sprawl over more compact development. Despite clear movement in the right direction, zero-emission vehicles are still more expensive to purchase than their fossil fuel–powered counterparts. Additionally, there is not enough infrastructure to inspire sufficient consumer confidence in the ability of EVs to get people where they need to go. Finally, there are some promising options for decarbonizing aviation and maritime shipping, but these solutions have not yet seen enough policy support to properly bring them from pilot and demonstration scale to commercial scale. Fortunately, all of these barriers can be addressed through concerted, coordinated action by governments, private funders, and manufacturers and purchasers of the suite of mobility vehicles.

Increase spending on alternative modes of transportation

Globally, public and private funds spent on transportation infrastructure are primarily dedicated to supporting roads and highways, which cater mainly to private automobiles and trucks. This is especially true in OECD countries. In the United States, for example, in the recent past, 80 percent of federal transportation dollars have gone to highway spending, whereas less than 20 percent is spent on active modes (walking, bicycling, and their variants) and public transit (Davis 2021). There is a relationship between the availability of infrastructure and modal share (Graham-Rowe et al. 2011), which means that in order to make alternative modes of transportation an alternative to car travel, there needs to be a shift in the way both public and private monies are spent in favor of low-carbon mode infrastructure, such as public transportation, walking, and cycling.

Some jurisdictions have begun to rethink how their citizens interact with their transport infrastructure. The countries of Israel and New Zealand, the U.S. states of California and Washington, and many cities have established vehicle travel reduction targets and regulations that require major transportation and land-use development projects be designed to support those goals (CAPCOA 2021; Litman 2022; Washington State Legislature 2008; Roberts 2019). The country of Wales has (at least temporarily) halted all highway expansion projects as a measure to achieve net-zero emissions by 2050, and Ireland has earmarked 20 percent of its infrastructure budget for walking and cycling (Adriazola-Steil et al. 2021; BBC News 2021). As of the end of 2019, governments around the world were investing $1.4 trillion in light-rail and metro projects under development—two-thirds of which was being spent in Asia, followed by the Middle East (10 percent), Europe (9.6 percent), North America (8 percent), Latin America (3.6 percent), and Africa (3 percent) (Hannon et al. 2020).

To achieve the necessary reductions in private car trips while improving overall accessibility, governments can increase their spending on both infrastructure and operations of alternative transport modes such as public transport, walking, and cycling and can also adopt transport demand-management policies combined with better zoning practices. In addition to reducing emissions, these reforms also help achieve economic and social goals by reducing total transportation costs and improving affordable mobility. Other actions could include more efficient road, parking, and vehicle pricing, so automobile travel is no longer underpriced and subsidized (Welle and Avelleda 2020).

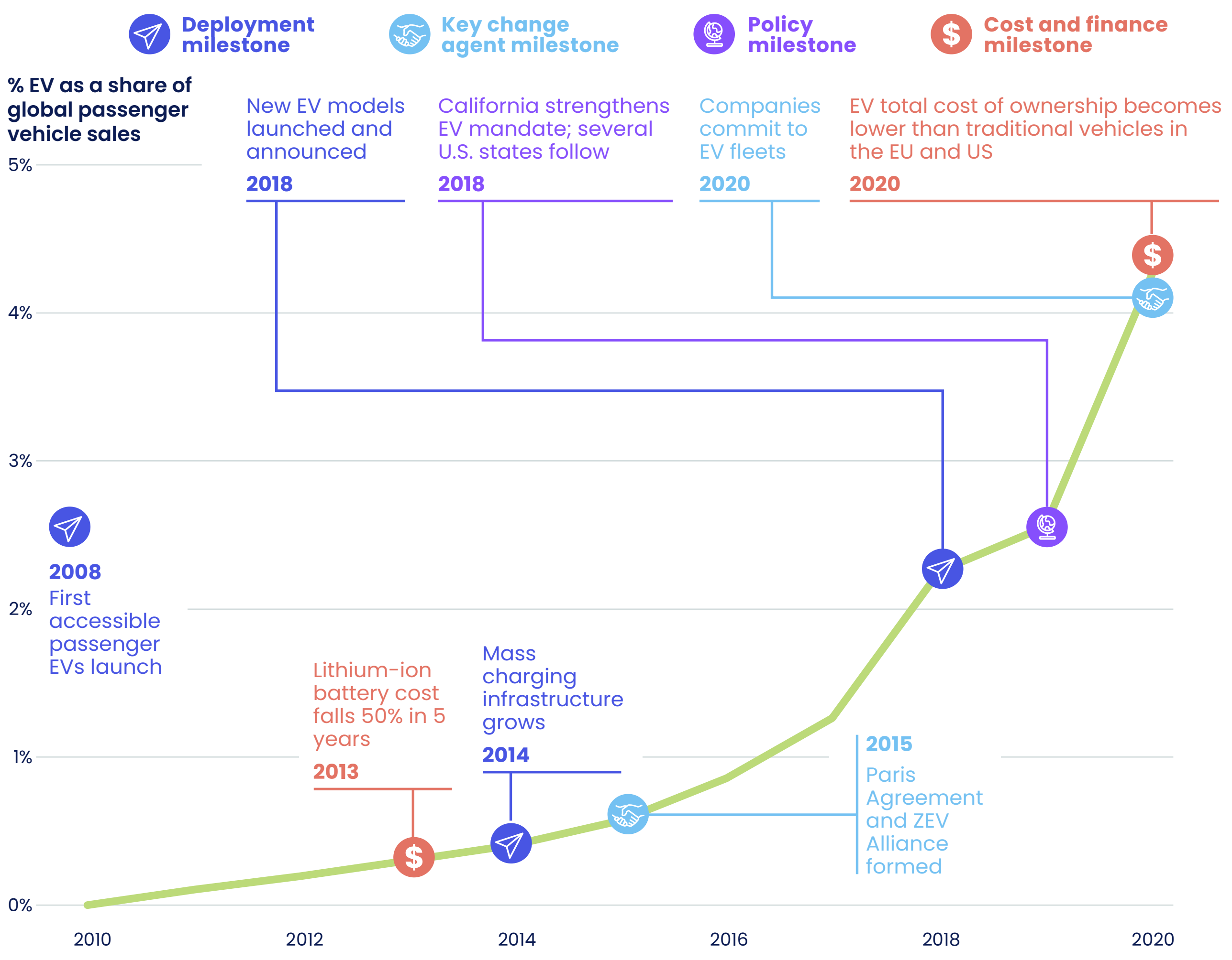
Reverse policies that incentivize sprawl and car-dependency and enact policies that promote compact cities

Today, both road allocation and pricing signals are weighted heavily toward the use of private cars and larger vehicles. Realigning regulations, policies, and incentives to assert cost parity between modes and space parity for travel rights of way would go a long way to transforming mode and vehicle choice of both people and the private sector, as well as improve mobility and access for populations that can't afford cars, or obtain a driver's license. These adjustments would transform the real and perceived marginal costs of choosing to travel by car or by other modes.

The use of private vehicles is currently subsidized by society, not only through direct government funding but also by shouldering the burden of negative externalities that car use generates. These include car crashes and air pollution that result in increased morbidity and mortality, time losses from increased congestion, and space use, among others. Reversing these subsidies and enacting policies that more closely reflect the true cost of automobility could go a long way to reducing these externalities. Policies such as car-parking and curb pricing that reflects market rates, penalties for high-polluting vehicles, registration taxes and restrictions, and policies such as (de) congestion pricing, which imposes a fee for vehicles traveling on congested roads or into congested areas, can be tailored to correctly price the costs of congestion and/ or local pollution generated by car use. Efficient pricing revenues can then be used to improve and encourage efficient transportation modes by, for example, improving pedestrian and bicycling facilities, and funding public transport. London implemented a congestion charge in 2003, and there is evidence that it has reduced traffic, reduced pollution, and increased property values in the immediate area of the zone (Tang 2021; Green et al. 2020). Other policies, such as low- or zero-emission zones, can be implemented to restrict the entrance of combustion engine vehicles to specific areas of cities, where there might be a need to reduce air pollution. About 50 cities, mainly in Western Europe but also a few in Asia, have implemented near-zero or zero-emission zones (Cui et al. 2021). In theory, this should reduce congestion and could increase public transit use, at least in the short term.

Another of the main barriers to reducing transport demand and shifting to lower-carbon modes is land-use decisions. While changes to land use (e.g., zoning laws) take time to alter the physical world, it is important that these decisions consider the implications they will have on transportation demand. Higher-density, mixed-use, and transit-oriented development will favor shorter trips that are more feasible using more efficient modes such as public transport, walking, and cycling. As urban populations grow, careful planning around density will reduce emissions from the transportation sector in the long run. In places like the United States where zoning decisions have already led to sprawl, cities such as Minneapolis are showing a pathway toward reversing some of its negative impacts by enacting legislation that can increase density and reduce sprawl while increasing housing supply (U.S. HUD 2021).

FIGURE 40 | Key milestones in the exponential growth of electric vehicle sales



Note: EV = electric vehicle; ZEV = zero-emission vehicle.

Source: Dennis (2021).

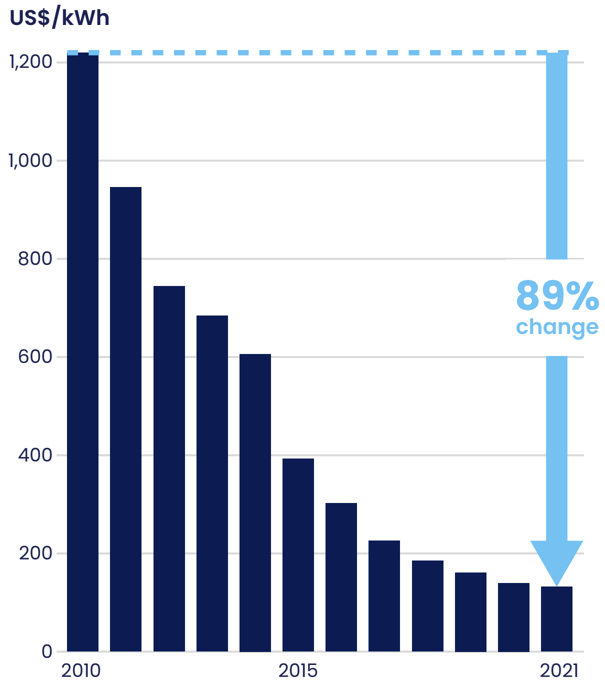
Ramp up pressure to switch to zero-emission vehicles

From the supply perspective, a common method of pushing decarbonization of vehicles is for governments to set sales mandates for manufacturers, where a percentage of their sales must be electric. In 2021, a coalition including 39 countries, 13 automakers, and dozens of other members of the automotive supply chain signed a pledge to work toward 100 percent global zero-emission car and van sales by 2040 ("COP26 Declaration on Accelerating the Transition to 100% Zero Emission Cars and Vans" 2022). By the end of 2021, 13 countries and 1 U.S. state had committed to 100 percent electric car sales, although target years varied from 2025 to 2050 (Wappelhorst 2021). Most recently, the European Union voted to end the sale of ICE cars in the bloc by 2035 (Abnett 2022). Only two countries and six U.S. states have set similar targets of 100 percent for MHDVs, but two additional countries and one Chinese province have set targets of between 50 percent and 90 percent (Wappelhorst and Rodríguez 2021b; Bliss 2022). Seven countries and one U.S. state have committed to 100 percent sales of zero-emission buses, and five countries and one U.S. state have set fleet goals between 2025 and 2050 (Wappelhorst and Rodríguez 2021a). Not all of these targets are legally binding restrictions or mandates, but setting a target at least sends a signal to industry of the government's intention, which is important so that manufacturers can make investments with some level of certainty about the direction of future regulation.

Automakers are also responding to increased interest in EVs, with General Motors, Honda, Jaguar, Mercedes-Benz, and Volvo all pledging to phase out the sale of ICE vehicles in the next 20 years and every major automaker pouring money into developing new EVs (Motavalli 2021). Figure 40 shows some key milestones, including regulations such as California's EV sales mandate and France's 2040 ICE vehicle sales ban, that have coincided with the growth of EVs through 2020. Although many automakers have repeatedly increased their commitments over the past few years, there is currently still a gap between their expected production and the share of electric cars required to meet government targets around the world (SLOCAT 2021, 2022). Additionally, major automakers and their trade groups sometimes simultaneously oppose policies that could accelerate transportation decarbonization, such as stringent fuel economy standards or ICE vehicle sales bans (InfluenceMap 2022).

The outstanding progress made by China on EV bus uptake over the last decade provides lessons for others to follow. The Chinese government began subsidizing public electric vehicles in 2009 to stimulate the domestic manufacturing industry and tackle urban air pollution, leading to a surge in electric bus sales from 1,000 in 2011 to over 100,000 in 2017 (Government of China 2009; BNEF 2021b). It also offered generous purchase subsidies and tax breaks in conjunction with local governments (ITDP 2018). Purchase subsidies have also partially driven large increases in electric car sales in Latin America in 2021 and 2022, albeit from a lower base (Argus Media 2022). In addition to changing the marginal costs of movement, as outlined above, we need to address one-time capital costs of vehicle acquisition. As shown in Table 7, the total cost of owning an electric car is quickly approaching parity with ICE counterparts in some European countries, although this point will arrive later in developing countries. The total cost of ownership for urban or regional zero-emission trucks is approaching parity just as quickly in China, Europe, and the United States (with India not too far behind), although long-haul trucks will reach parity much closer to 2050 (Mission Possible Partnership 2022b). At the same time, the current up-front cost of zero-emission passenger vehicles, buses, and medium- and heavy-duty vehicles is higher than that of their internal combustion engine counterparts, and the consumer choosing a vehicle simply based on purchase price would be hard-pressed to buy a cleaner vehicle. As shown in Figures 41 and 42, however, battery prices have fallen dramatically in the past decade and are expected to bring light-duty battery electric vehicles into up-front price parity with their ICE counterparts in some major markets between 2022 and 2030 without subsidies, but it will take time to reach that goal globally and for the average supply to meet that price (BNEF 2021b).

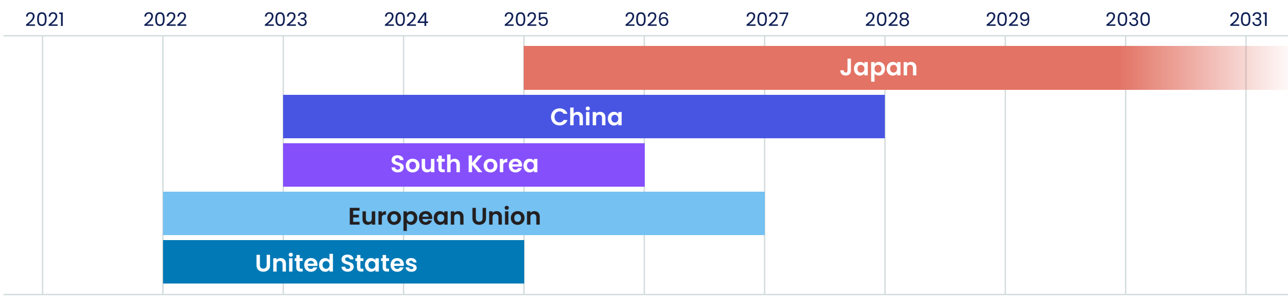
FIGURE 41 | Volume-weighted average lithium-ion pack price



Note: $/kWh = dollar per kilowatt-hour.

Source: BNEF (2021a), reprinted with permission from Bloomberg New Energy Finance.

FIGURE 42 | Light-duty electric vehicle price parity in major markets



Note: "Price parity" refers to up-front cost without subsidies and not total cost of ownership.
Source: BNEF (2021b), reprinted with permission from Bloomberg New Energy Finance.

Because two- and three-wheelers are much more prevalent in many parts of the world than cars are (UNEP n.d.), it will be important to transition these vehicles to electric alternatives, especially to improve local air pollution. Although incentives for electric two- and three-wheelers are not as prevalent as those for electric cars, they are sometimes included in broader EV incentives—in India, for example, the government will cover about $188 per kWh for a two-wheeler and $125 per kWh for a three-wheeler (NITI Aayog n.d.).

Although EVs are expected to reach price parity with ICE vehicles over the next decade, waiting for the economics to align naturally does not put the world on a path to 1.5°C on a sufficiently short timeline—and in a world where fossil fuel subsidies totaled $5.9 trillion in 2020, some policies are actively working against this alignment (IMF 2021a). Demand-side measures to increase EV adoption in the short term, including consumer subsidies and regulations, such as reduced road usage fees or purchase taxes, can help make EV purchasing more attractive (Wee et al. 2018). Notably, incentivizing electric car purchasing in this way could conflict with efforts to reduce congestion or increase the use of public transport.

Providing incentives to private EV purchasers could direct a disproportionate share of government spending to high-income households. Indeed, this has historically been the case. Careful, system-level planning could help address these inequities, including by evaluating subsidy types—the U.S. state of California, for example, has seen success targeting grants at low-income residents instead of tax credits (California Climate Investments 2021)—and by directing money toward other modes of transportation that will benefit all residents.

Build out enabling infrastructure for zero-emission vehicles, planes, and ships

In surveys of car-dependent Global North consumers about purchasing electric cars, respondents often cite anxiety about insufficient access to EV charging as a reason not to drive an EV (Pevec et al. 2020). Further, studies have shown that there is a fairly well-established relationship between the existence of EV charging and EV adoption (Hall and Lutsey 2017). In the United States, 88 of the top 100 most populous metropolitan areas have less than half the public and workplace charging infrastructure needed to meet their expected EV growth by 2025 (Nichols et al. 2019). In the United Kingdom, London and Scotland have seen charging infrastructure deployment growth on track with 2030 goals, but most of the rest of the country has less than 20 percent of the infrastructure it will need (Nichols and Lutsey 2020). Efforts to speed up charging infrastructure build-out require careful collaboration among governments, utilities, charging companies, and local communities (Hall and Lutsey 2017). These efforts can include redesigning utility rates to make public charger maintenance more attractive and offering land to charger networks at reduced prices (Klock-McCook et al. 2021).

A build-out of public charging could advantage certain communities over others if not planned in an equitable way. Further, there could even be unintended consequences of rate design. In 2018, UK consulting firm Stantec highlighted that EV owners with off-street parking and home charging could charge their EVs for about £7 per 300 miles, whereas those without access to home chargers (such as residents of multifamily apartment buildings) needed to rely on limited public charging costing about £20 per charge (Witohalls and Riggall 2018). Efforts to alleviate these sorts of inequalities would require targeted support for charging infrastructure in low-income areas and measures to eliminate cost premiums at public charging points.

But charging is not just needed for privately owned cars. It is necessary for all electrified vehicles, including medium- and heavy-duty freight and commercial vehicles, electric airplanes, and electric ships. These will all require different solutions for charging due to their use profiles and their power demands. Alongside charging infrastructure, hydrogen fueling infrastructure will be important to build for hydrogen-powered vehicles, planes, and ships.

Reorient shipping and aviation policies to enable widespread use of sustainable aviation fuels and zero-emission fuels

Zero- or even low-emissions options for aviation are nascent and in the early emergence stage of development. Currently, the best-developed solutions are sustainable aviation fuels, including hydrogenated esters and fatty acids, gasification + Fischer-Tropsch synthesis, alcohol-to-jet, and power-to-liquid production. Today, SAFs' share of total aviation fuel is less than 0.1 percent, all of which is made from hydrogenated esters and fatty acids. Typically, biofuels (particularly crop-derived fuels) can be unsustainable because they can compete with food production for water and land, divert food crops away from feeding the hungry, and alter local ecosystems (Searchinger et al. 2019b). Because of this, experts disagree on the suitability of biofuels as a sustainable aviation fuel. 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).

Three options that appear to be promising for decarbonizing aviation are power-to-liquid fuels, green hydrogen, and batteries. A recent study from Germany's energy agency finds that in a scenario that eliminates fossil jet fuel and optimizes for cost, fuels made from green hydrogen and CO_2 captured via direct air capture could meet more than half of future aviation fuel demand in the United States and European Union, while direct use of hydrogen would meet 34 percent and battery electricity would meet 9 percent (Micheli et al. forthcoming). The contribution of biofuels is only about 1 percent in this scenario. It is important to consider, however, that the production cost of fuels derived from electricity is highly dependent on future electricity prices (and the electricity being zero-carbon), and producing these fuels will require significant R&D investment to bring down costs to compete with their fossil fuel counterparts (Malins 2017). Additionally, using CO_2 from direct air capture would be a carbon-neutral exercise—removing CO_2 from the atmosphere and rereleasing it when the fuel is burned—rather than a carbon-negative exercise, such as storing the captured CO_2 underground. The use of direct air capture also may have distributional impacts on communities' land and water use, as discussed in Section 8.

Hydrogen and battery electric planes are in development, but they are still in the early stages and will require time to reach maturity and commercial adoption. Batteries are only suitable for very short-haul flights because of their high weight-to-energy-density ratio (Gray et al. 2021), and over those distances, the sustainable alternative may be traveling by train where this infrastructure exists. Airbus has pledged to have a hydrogen plane on the market in 2035, while Boeing's chief executive officer has questioned its viability between now and 2050 (Airbus 2022; Singh 2021).

Zero-carbon options for shipping are also in the early emergence stage of development. Ammonia, biofuels, hydrogen, and batteries are generally considered the major technology options that could become available to decarbonize shipping (IPCC 2022b). Green hydrogen and ammonia (which are produced using renewable energy) are widely viewed as the most promising fuels due to their favorable life-cycle GHG emissions, economics, and scalability (Englert and Losos 2021; ETC 2019c; BNEF 2020; Victor et al. 2019; Shell and Deloitte 2020). However, some companies such as shipping giant Maersk are betting big on methanol made from green hydrogen and captured carbon (Frangoul 2021). Green ammonia is generally favored over hydrogen because it requires less onboard storage, is easier to handle as it requires less cooling, and is less flammable (Englert and Losos 2021). However, governments across the world have shown a renewed interest in hydrogen as a tool for decarbonization in the past few years, and although most of this interest has gone into road vehicles, power, and industry, governments are increasingly turning to hydrogen and hydrogen-derived fuels such as ammonia for shipping fuels. As of the first quarter of 2022, 88 pilot and demonstration projects to produce zero-emission shipping fuels received public funding, about half of which were hydrogen projects (Global Maritime Forum 2022).

Developing, commercializing, and scaling these solutions requires a policy environment that allows for these fuels to be competitive and attractive for use. Alongside the ReFuel EU proposal for aviation, the European Union is considering a FuelEU program for maritime transportation that would require large ships to reduce GHG intensity of onboard energy by 2 percent in 2025, increasing to 75 percent by 2050 (European Council 2022). Additionally, the European Union is considering extending its emissions trading system to include maritime emissions. This type of system (or a similar mechanism) could be expanded globally. For example, an analysis from the consultancy UMAS (2022a) suggests that decarbonizing global shipping through a carbon price could be accomplished at $191 per tonne.

Several operational and design changes, such as speed reductions and weight reductions, can decrease (but not eliminate) emissions and will likely be part of the solution (Mallouppas and Yfantis 2021). However, there are often associated trade-offs, including longer travel times that offset the fuel savings benefits of slower speeds.

SECTION 6

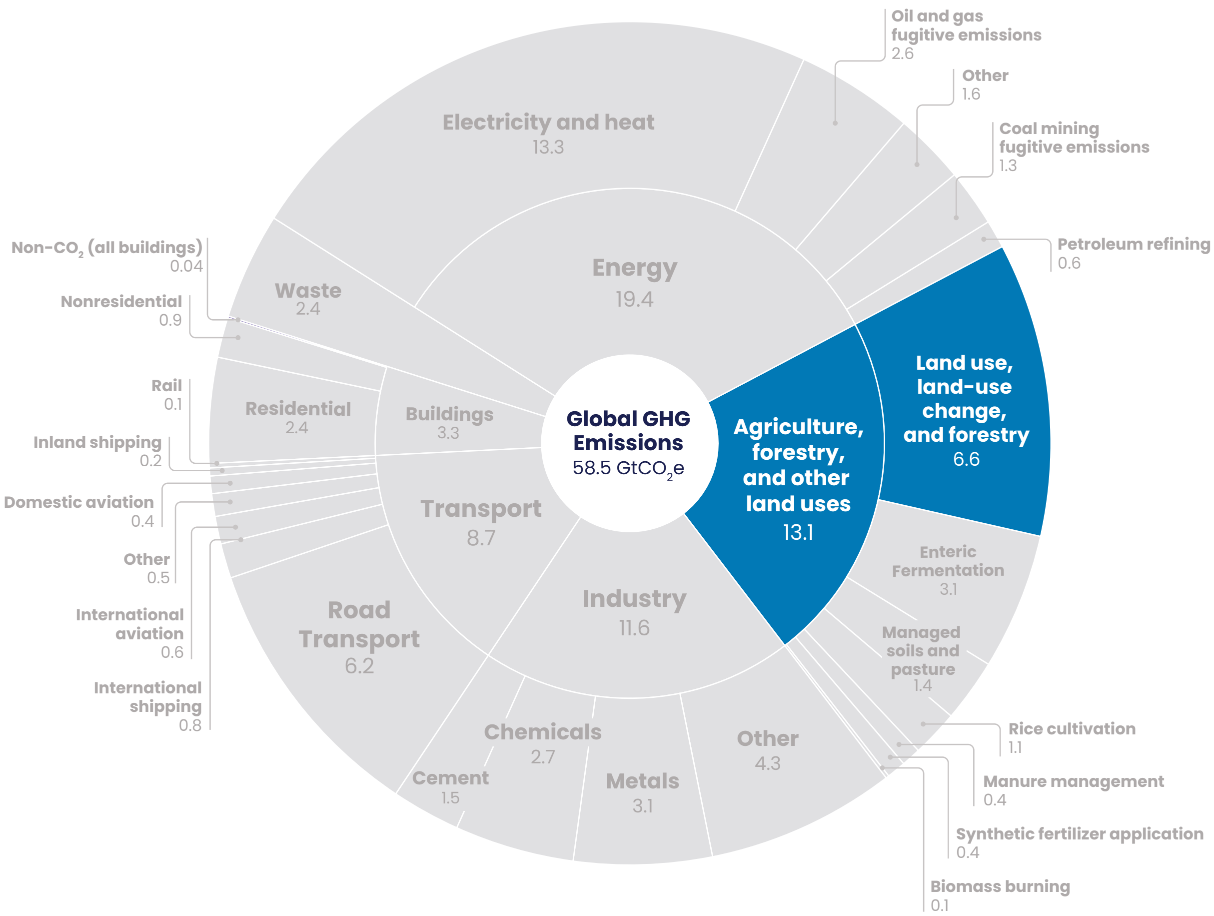
Forests and Land

Humanity depends on healthy ecosystems, which deliver life-sustaining services that range widely from provisioning food to regulating water quality to supporting livelihoods (IPCC 2019; IPBES 2019; UNCCD 2017). Yet how people interact with these lands also plays an integral role in the global climate system. Destroying and degrading the planet's ecosystems—particularly forests, peatlands, coastal wetlands, and grasslands—releases greenhouse gases into the atmosphere, while restoring and sustainably managing these lands can enhance carbon sequestration, as well as reduce GHG emissions (IPCC 2022b, 2019a).

In 2019, agriculture, forestry, and other land uses (AFOLU) emitted over one-fifth of GHGs globally (13 $GtCO_2e$) (Figure 43), with net anthropogenic releases of carbon dioxide, methane, and nitrous oxide increasing by an average of 1.6 percent per year over the last decade (IPCC 2022b). CO_2 emissions, which primarily stem from land use, land-use change, and forestry, accounted for about half of all GHG emissions from AFOLU in the same year (IPCC 2022b).[33] Yet uncertainties in nationally reported data, limitations in the representation of land management across global models, and differences in how methods conceptualize the "anthropogenic" CO_2 flux from unmanaged and/or managed lands make it challenging to determine even the direction of this long-term trend in net anthropogenic CO_2 emissions with confidence. Some approaches, such as the average from three global book-keeping models, indicate a slight increase in net CO_2 emissions since 2000 (Figure 44),[34] while others that rely on nationally reported data, such as National Greenhouse Gas Inventories, suggest the opposite trend. But when considering CO_2 fluxes from both managed and unmanaged lands' responses to climate change, other anthropogenic environmental changes, and natural climate variability, the science is much clearer—land remains a net carbon sink globally, sequestering one-third of CO_2 emissions from all human activities to help slow climate change (IPCC 2022b).

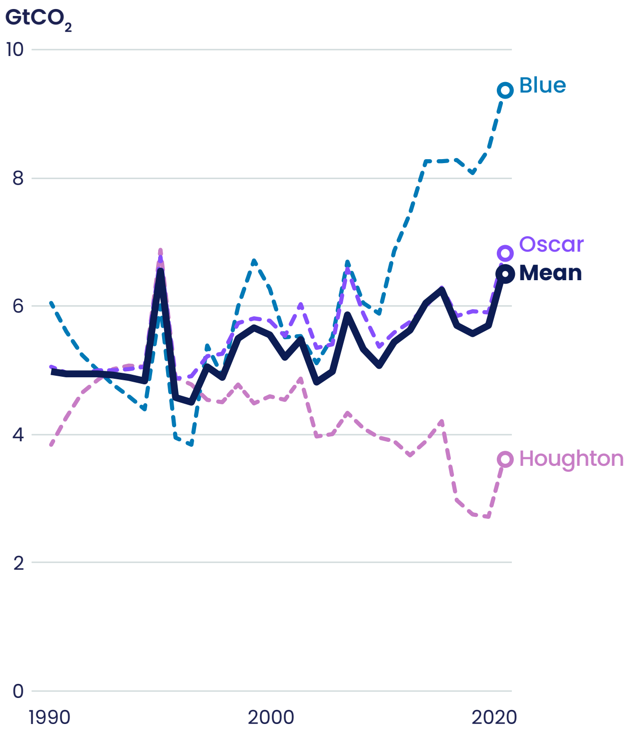
Holding global temperature rise to 1.5°C will require immediate action to protect the world's natural carbon sinks and stores, as well as the rapid scale-up of global

FIGURE 43 | AFOLU's contribution to global GHG emissions in 2019



Notes: CO_2 = carbon dioxide; GHG = greenhouse gas; $GtCO_2e$ = gigatonnes of carbon dioxide equivalent.
Source: Minx et al. (2022), described in Minx et al. (2021) and used in IPCC (2022b).

FIGURE 44 | Global net anthropogenic CO_2 emissions from land use, land-use change, and forestry



Notes: CO_2 = carbon dioxide; $GtCO_2$ = gigatonnes of carbon dioxide. Blue, Houghton, and Oscar are three separate book-keeping models that have been averaged to provide a global mean estimate.
Source: Minx et al. (2022), described in Minx et al. (2021) and used in IPCC (2022b).

efforts to restore and sustainably manage these ecosystems. Together, these land-based measures across forests, peatlands, coastal wetlands, and grasslands[35] can mitigate between 4.2 $GtCO_2e$ and 7.3 $GtCO_2e$ per year at relatively low costs (<\$100/tCO_2e)[36] from 2020 to 2050 (IPCC 2022b), a range that is also in line with limiting warming to 1.5°C (Roe et al. 2019). Yet recent global progress made in deploying these measures remains insufficient—none of the indicators assessed for forests, peatlands, and mangroves,[37] specifically, are on track to achieve their 2030 targets (Table 8). And due to data limitations in assessing their progress, targets and indicators for improved forest management and grassland fire management are excluded.[38]

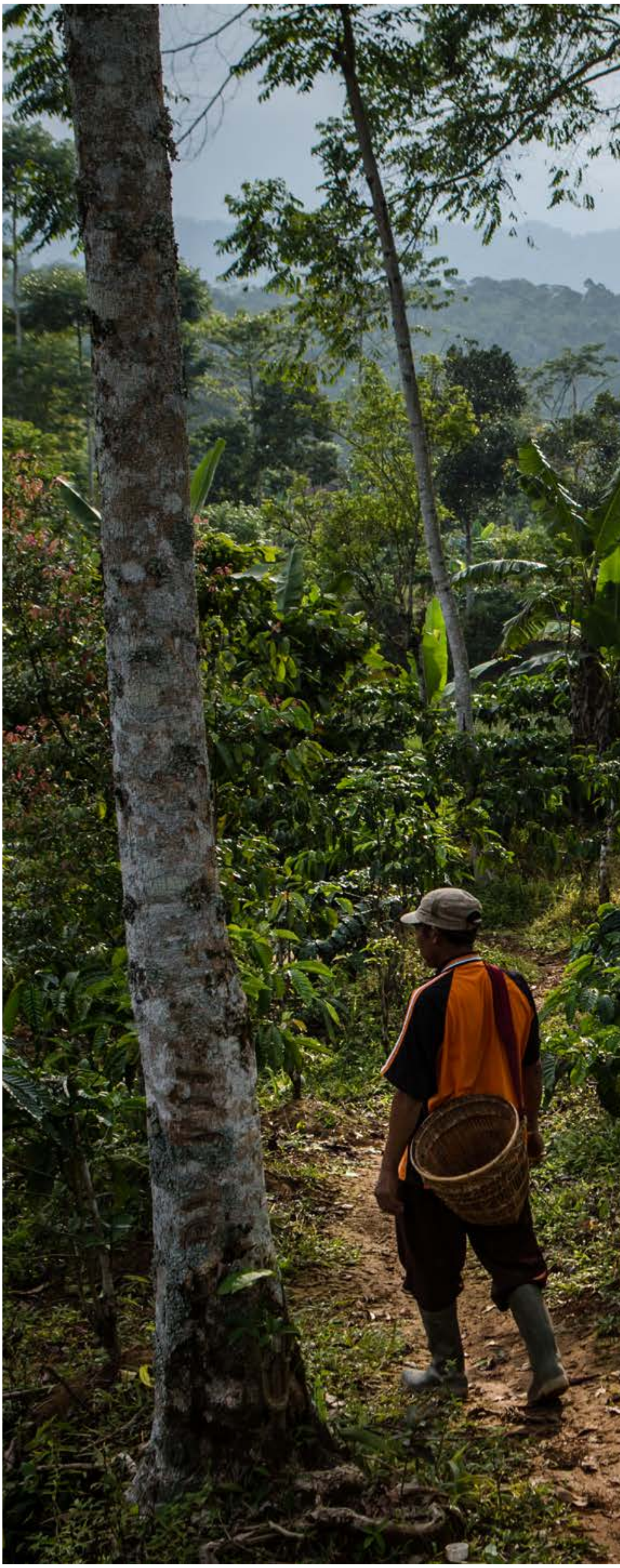


TABLE 8 | Summary of global progress toward forests and land targets

INDICATOR	MOST RECENT DATA POINT (YEAR)	2030 TARGET	2050 TARGET	TRAJECTORY OF CHANGE	ACCELERATION FACTOR	STATUS
Deforestation (Mha/yr)	5.7 (2021)	1.9	0.31		2.5x[a]	
Reforestation (total Mha)	130 (total gain, 2000–2020)	100	300		1.5x[b]	
Peatland degradation (Mha/yr)	0.78 (annual average, 1990-2008)	0	0		Insufficient data	
Peatland restoration (total Mha)	No historical data	15	20		Insufficient data	
Mangrove loss (ha/yr)	32,000[c] (annual average, 2017-2019)	4,900	N/A		N/A; U-turn needed	
Mangrove restoration (total Mha)	0.015[d] (total gain, 1999–2019)	0.24	N/A		Insufficient data	

Notes: ha/yr = hectares per year; Mha/yr = million hectares per year; total Mha = total million hectares. 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 is used to calculate the linear trendline where possible.

[a] To calculate this acceleration factor, a linear trendline was estimated using 7 years of data from 2015 to 2021, rather than 10 years of data due to temporal inconsistencies in the data before and after 2015 (Weisse and Potapov 2021). See Box 5 and Schumer et al. (2022) for more information.

[b] To calculate this acceleration factor, the average annual rate of change across the most recently available time period (2000–2020) is used to estimate the historical rate of change, rather than a linear trendline due to data limitations and following Boehm et al. (2021).

[c] Historical data from Murray et al. (2022), which estimated mangrove loss for six three-year epochs. Gross loss was divided by the number of years in each epoch to determine the average annual loss rate, and a linear trendline was calculated using these data.

[d] Murray et al. (2022) estimated that 0.18 Mha of gross mangrove gain occurred from 1999 to 2019, only 8 percent of which can be attributed to direct human activities, such as mangrove restoration. Accordingly, this report does not use gross mangrove gain to approximate mangrove restoration. We estimate the most recent data point for mangrove restoration by taking 8% of the total gross mangrove gain from 1999-2019. See Schumer et al. (2022) for more information.

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

Status of forests and land indicators

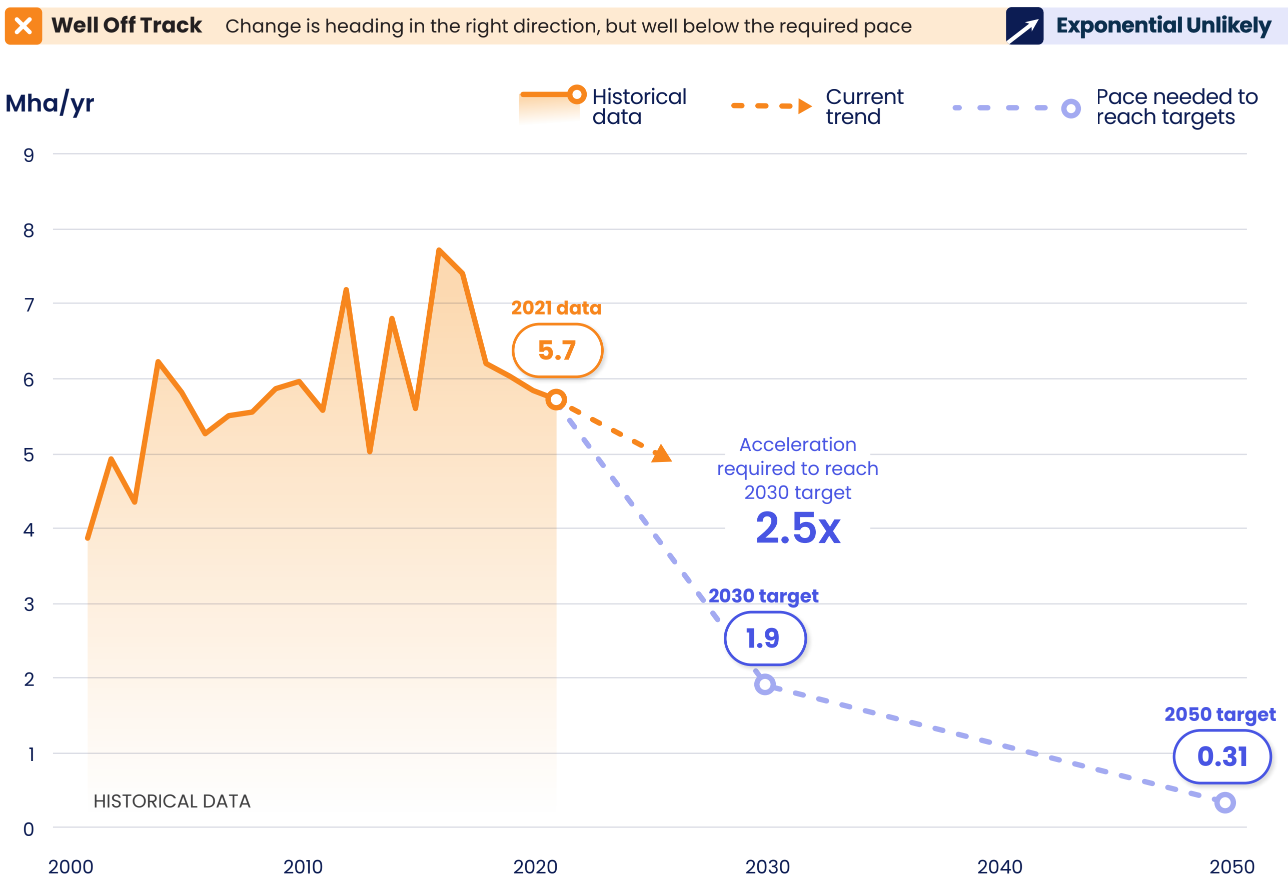
FORESTS AND LAND INDICATOR 1: Deforestation (Mha/yr)

- **Target**: The annual rate of gross deforestation globally declines to 1.9 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), deforestation accounts for nearly half of total GHG emissions from AFOLU (IPCC 2022b). From 2001 to 2021, the annual rate of gross deforestation rose by approximately 48 percent, and in 2021 alone the world converted 5.7 million hectares (Mha) of forests to new, nonforest land uses, emitting 3.3 $GtCO_2e$ (see Box 5 for how we estimate deforestation). Although this represents a decline from 5.8 Mha in 2020,[39] annual deforestation rates are not decreasing rapidly enough (Hansen et al. 2013; Curtis et al. 2018; Turubanova et al. 2018; Tyukavina et al. 2022), with recent progress remaining well off track.[40] Holding global warming to 1.5°C will require rates of deforestation to fall 70 percent by 2030 and 95 percent by 2050, relative to 2018 levels (Roe et al. 2019). To reach this near-term target, declines in annual deforestation rates must accelerate 2.5-fold over the next decade (Figure 45).

Nearly 97 percent of deforestation from 2001 to 2021 occurred in the tropics (WRI 2022c), and since 2015, three countries—Brazil, Indonesia, and the Democratic Republic of the Congo—have accounted for over half of all deforestation globally. However, trends within these countries vary considerably. Indonesia, for example, has witnessed ongoing declines in deforestation and associated emissions since 2017. Meanwhile, deforestation in Brazil has remained relatively high since 2016, reversing declines observed in the early to mid-2000s, while rates in the Democratic Republic of the Congo also have increased since 2019 (Hansen et al. 2013; Curtis et al. 2018; Turubanova et al. 2018; Tyukavina et al. 2022).

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 is used to calculate the linear trendline where possible. For this indicator, however, we calculated a 7-year trendline using data from 2015 to 2021 due to temporal inconsistencies in the data before and after 2015 (Weisse and Potapov 2021). See Box 5 and Schumer et al. (2022) for more information.

Sources: Historical data from Global Forest Watch, using datasets updated to 2021 (Hansen et al. 2013; Curtis et al. 2018; Turubanova et al. 2018; Tyukavina et al. 2022); 2030 and 2050 targets adapted from Roe et al. (2019). See Box 5 for description of methods used to estimate deforestation.

BOX 5 | How do we estimate deforestation?

Publicly available, medium-resolution satellite imagery has allowed for major advances in global forest monitoring. In 2013, researchers from the University of Maryland published a dataset based on Landsat satellite imagery that maps global tree cover change, available on Global Forest Watch, and they have been updating it annually since the initial publication (Hansen et al. 2013). These data map "tree cover," which we define here as woody vegetation with a height of at least 5 meters and a 30 percent tree canopy density at the scale of a 30 × 30 meter pixel,[a] as well as the complete removal or mortality of tree cover, known as tree cover loss.

Tree cover loss can occur for a variety of natural or anthropogenic reasons, including windfalls, harvesting of wood from timber plantations, fires, or conversion of forests to other land uses, among other causes. Deforestation, however, typically refers to the permanent conversion of natural forest cover to new, nonforest land uses (WRI 2022a, 2022c). Because measuring deforestation requires knowing what will happen to the land following tree cover loss, it can be challenging to monitor annually. Therefore, our estimate relies on a proxy that combines tree cover loss data with additional contextual datasets that provide information on the drivers of loss.

(continues)

[a] Hansen et al. (2013) estimate tree canopy density, ranging from 0 percent to 100 percent, for the year 2000 for each 30 m pixel in their global map of forest extent. Therefore, the data can be filtered using any tree canopy density threshold. For this indicator, we use a 30 percent tree canopy density threshold.

BOX 5 | How do we estimate deforestation? (continued)

To estimate deforestation, we use a proxy indicator that combines four datasets available on Global Forest Watch: tree cover loss (Hansen et al. 2013), tree cover loss by dominant driver (Curtis et al. 2018), tree cover loss due to fire (Tyukavina et al. 2022), and humid tropical primary forest extent (Turubanova et al. 2018). This proxy includes all tree cover loss that was not due to fire (Hansen et al. 2013; Tyukavina et al. 2022) in areas whose dominant driver, as defined by Curtis et al. (2018), was classified as commodity-driven deforestation, urbanization, or humid tropical primary forest loss (Turubanova et al. 2018) due to the expansion of shifting agriculture. We removed any areas that overlapped with data on mangrove loss (Murray et al. 2022) to avoid double-counting that loss under both the deforestation and mangrove loss indicators.

Tyukavina et al. (2022) assign a likelihood of loss due to fire to each 30-meter tree cover loss pixel mapped by Hansen et al. (2013) and define tree cover loss due to fire as areas where fire was the direct cause of tree cover loss. This can include natural or human-ignited fires, such as wildfires, intentionally set fires, or escaped fires from human activities, such as hunting or agriculture. It does not include burning of felled trees, since the direct cause of loss in these cases is mechanical removal. Therefore, trees that are cut down and later burned to clear land for agriculture would not be classified as tree cover loss due to fire in this dataset (Tyukavina et al. 2022). Removing tree cover loss due to fire allows us to better observe trends in permanent deforestation without the interannual variability linked to extreme weather events, such as fires exacerbated by El Niño events in humid tropical forests across parts of Southeast Asia and South America in 2015–16 (Weisse and Goldman 2017). It is important to recognize, however, that even though fires often do not lead to a permanent land-use change, they are still an important source of GHG emissions. In tropical forests—where fires are not a natural part of ecosystem dynamics—climate change impacts, such as more frequent droughts, longer dry seasons, and hotter temperatures, combined with the biophysical effects from forest loss, can increase fire risk, lower resilience, and impede recovery of forests, potentially reducing carbon storage and removal and increasing emissions (Xu et al. 2020; Jolly et al. 2015; Wigneron et al. 2020; Lawrence et al. 2022; Boulton et al. 2022).

Once tree cover loss due to fire is removed from the tree cover loss data, we use data on the dominant driver of tree cover loss from Curtis et al. (2018), updated through 2021, to filter tree cover loss by driver categories that are more likely to represent a permanent conversion of forest cover to new, nonforest land cover or land uses. Curtis et al. (2018) classify tree cover loss within 10 × 10 kilometer grid cells into five categories that represent the dominant driver of loss within each grid cell: commodity-driven deforestation, forestry, shifting agriculture, urbanization, and wildfire. Tree cover loss due to forestry, wildfire, and shifting agriculture outside of humid tropical primary forests are considered losses that are more likely to be temporary, often followed by forest regrowth, and are not included in our deforestation proxy. Commodity-driven deforestation, urbanization, and shifting agriculture in humid tropical primary forests are considered more likely to represent permanent deforestation and are included in our deforestation proxy. Although shifting agriculture, as defined by Curtis et al. (2018), is broadly more likely to be considered a temporary disturbance, where tree cover is cleared for agricultural production and then abandoned to allow trees to regrow, we include shifting agriculture in humid tropical primary forests (Turubanova et al. 2018) due to the long-term impacts of primary forest lost (Goldstein et al. 2020; Gibson et al. 2011). Tree cover loss due to shifting agriculture in humid tropical primary forests represents approximately 22 percent of all tree cover loss due to shifting agriculture globally (Curtis et al. 2018; Turubanova et al. 2018; Hansen et al. 2013).

The Hansen et al. (2013) tree cover loss dataset has been improved over time through annual updates to the original dataset, including algorithm adjustments that increase detection of smaller-scale disturbances, as well as changes in satellite image availability with the launch of new Landsat satellites (Weisse and Potapov 2021). Therefore, certain types of forest disturbances, such as selective logging and small-scale agriculture, that may not have been detected in the original 2001–12 tree cover loss data may be detected in annual updates. Due to these data inconsistencies, we use a 7-year trendline from 2015 to 2021 to calculate the linear trendline for this indicator, as changes to the methodology and satellite imagery used to create the data have been minimal since 2015.

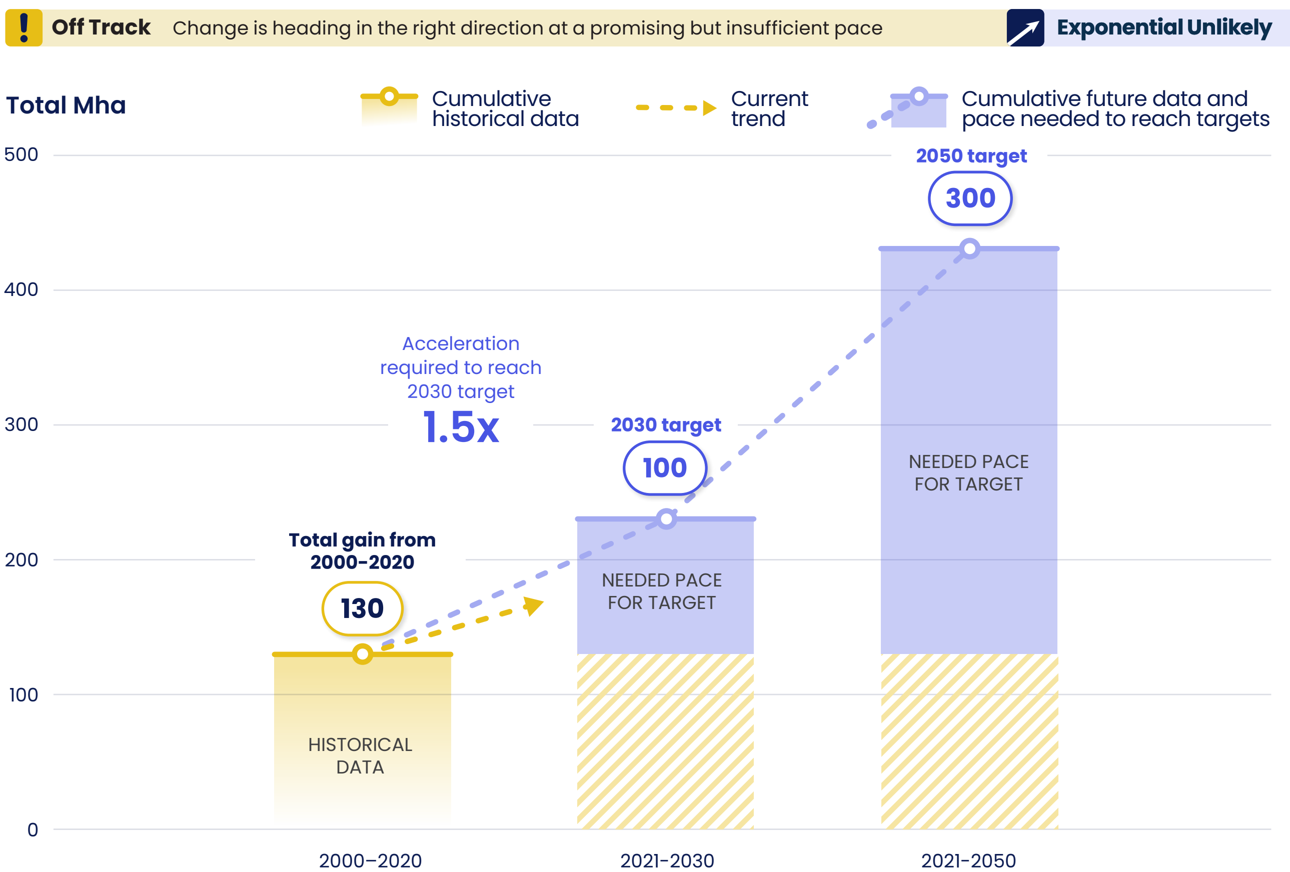
FORESTS AND LAND INDICATOR 2:
Reforestation (total Mha)

- **Target**: Reforestation occurs across a total of 300 Mha between 2020 and 2050, reaching 100 Mha by 2030.[41]

All modeled pathways that limit global temperature rise to 1.5°C with no or limited overshoot require carbon dioxide removal, and reforestation represents a readily available, relatively cost-effective approach that can deliver additional benefits when implemented appropriately (IPCC 2022b). Yet due to data limitations, assessing progress toward reforestation targets remains challenging. Available remote sensing data on the gross area of tree cover gain, a proxy for reforestation, indicate that a total of 130 Mha experienced tree cover gain from 2000 to 2020 globally (Potapov et al. 2022a).[42] However, these data may include tree cover gain that, although potentially beneficial to climate mitigation, is typically not defined as reforestation and would not count as progress toward these targets, including regrowth after harvesting across already established plantations and afforestation on historically nonforested lands (WRI 2022b). Although annual data on tree cover gain are not available, historical cumulative data from 2000 to 2020 indicate that global progress made in reaching this near-term target is off track[43] and will require a 1.5-fold acceleration to help hold warming to 1.5°C (Figure 46).

It is important to note that reforestation does not always equate to forest restoration. Reforestation describes the shift from nonforest cover to forest cover across lands where forests historically occurred, including, for example, natural forest regrowth, assisted natural regeneration, and the establishment of plantation forestry (Roe et al. 2021; IPCC 2022b). Forest restoration, however, goes beyond reestablishing trees to prioritize the recovery of forests' ecological functions (IPCC 2022b). When implemented appropriately, reforestation can achieve similar aims, but if efforts focus primarily on planting nonnative tree species or expanding monocultures, it can generate a range of adverse ecological impacts (IPCC 2022b).

FIGURE 46 | Historical progress toward 2030 and 2050 targets for reforestation



Notes: Mha = million hectares. Following Boehm et al. (2021) and due to data limitations, the average annual rate of change across the most recently available time period (2001–2020) is used to estimate the historical rate of change, rather than a linear trendline. See Schumer et al. (2022) for how we calculate acceleration factors and categorize progress.

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

FORESTS AND LAND INDICATOR 3:

Peatland degradation (Mha/yr)

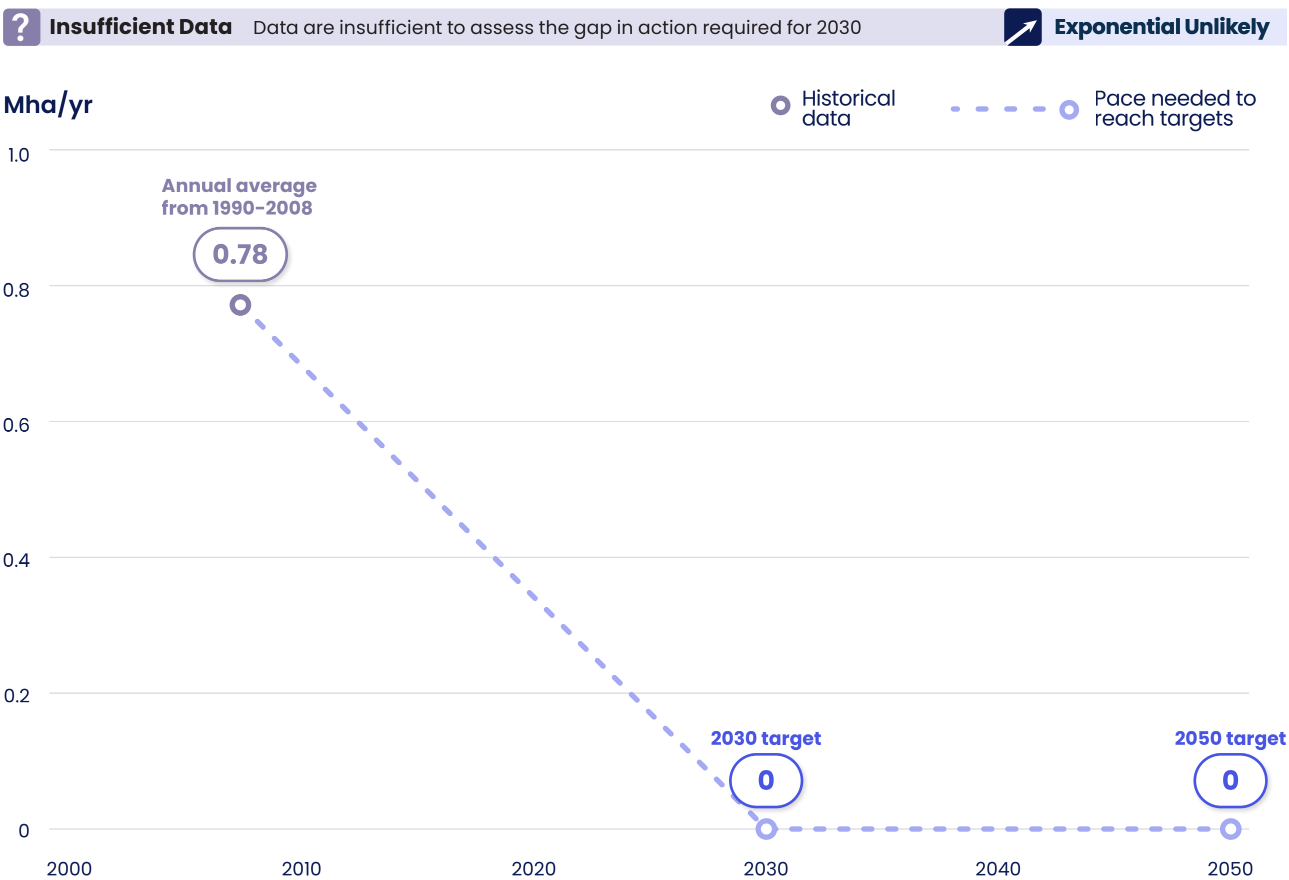
- **Target**: The annual rate of peatland degradation globally declines to 0 Mha/yr by 2030, with no additional degradation from 2030 to 2050.

Although they cover just 3 percent of the world's land (Xu et al. 2018), peatlands hold at least a fifth of soil organic carbon stocks globally (>600 GtC) (Yu et al. 2010; Scharlemann et al. 2014) and store an order of magnitude more carbon per hectare than the world's terrestrial forests (Temmink et al. 2022). These ecosystems also contain large stores of organic nitrogen, as waterlogged soils slow decomposition and allow carbon- and nitrogen-rich peat to accumulate over millennia. Peatland degradation, however, occurs when this water table is lowered, facilitating the oxidation of peat and, thereby, the loss of stored carbon (FAO 2020). Once this occurs, peatlands can emit carbon dioxide and nitrous oxide for decades to centuries until all peat is fully lost or wetted again (Wilson et al. 2016; Leifeld and Menichetti 2018).

Draining peatlands, in particular, increases the risk of peat fires, which can lead to additional GHG emissions (FAO 2020), while the ditches and canals constructed to drain these ecosystems also emit methane (FAO 2020).

From 1850 to 2015, as much as 51.4 Mha of peatlands were degraded, including 26.7 Mha across temperate and boreal regions and another 24.7 Mha in the tropics (Leifeld et al. 2019). But effectively halting worldwide peatland degradation by 2030 can help limit global temperature rise to 1.5°C (Griscom et al. 2017). Although annual data on the global extent of peatland degradation are insufficient to assess if recent progress has been made toward this near-term target (Figure 47), available evidence indicates that draining peatlands for agriculture accelerated from 1990 to 2019 in Southeast Asia (Conchedda and Tubiello 2020), a region that contains much of the world's tropical peatlands.

FIGURE 47 | Historical progress toward 2030 and 2050 targets for peatland degradation



Note: Mha/yr = million hectares per year.

Source: Historical data and the 2030 and 2050 targets are adapted from Griscom et al. (2017).

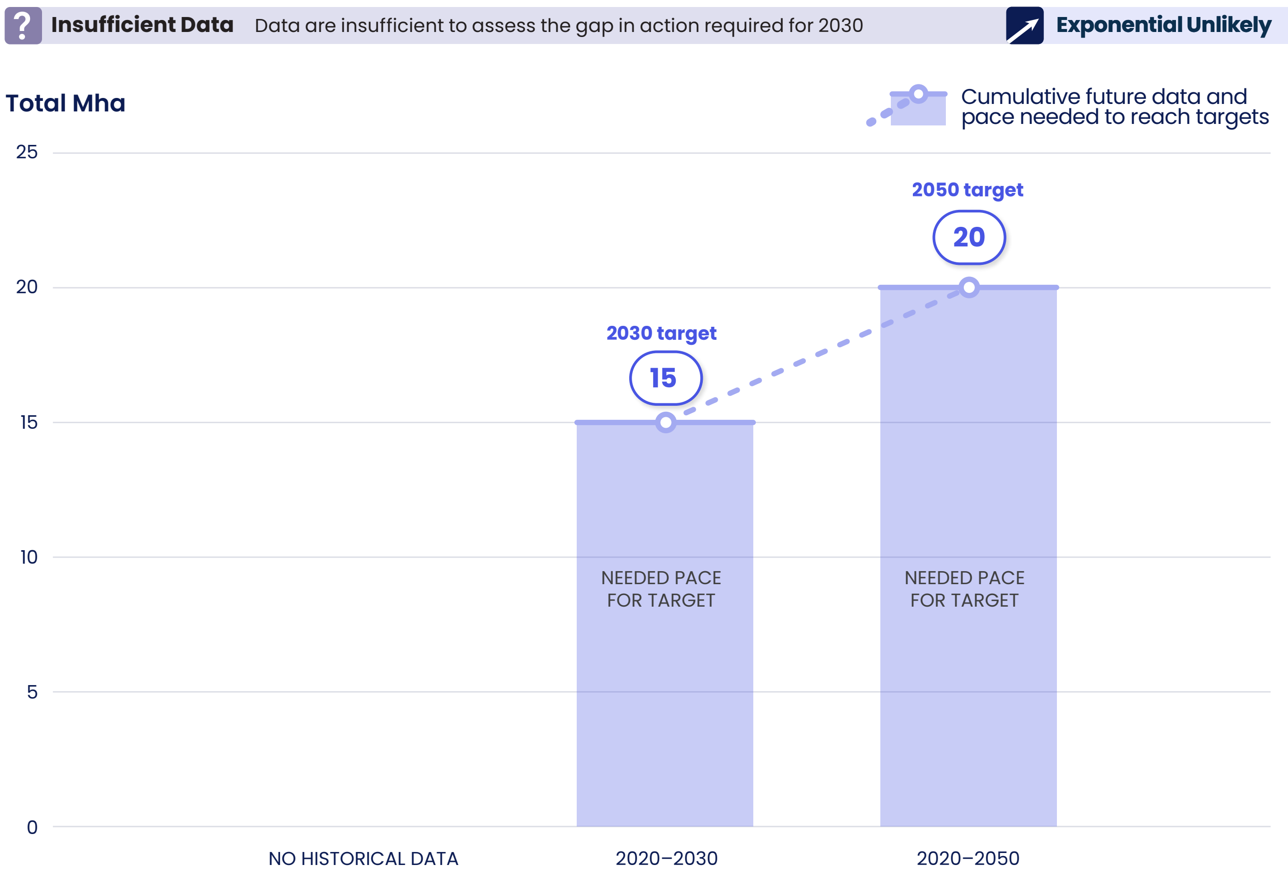
FORESTS AND LAND INDICATOR 4:

Peatland restoration (total Mha)

- **Target**: Worldwide, peatland restoration occurs across a total of 20 Mha of degraded peatlands between 2020 and 2050, reaching 15 Mha by 2030.[44]

In 2015, degraded peatlands emitted an estimated 1.5 $GtCO_2e$ annually (excluding GHG emissions from peat fires)—roughly equivalent to Brazil's total GHG emissions in 2019 (Humpenöder et al. 2020; ClimateWatch 2022). The potential to avoid these GHG emissions by restoring peatlands depends on how they were degraded (e.g., drainage, burning, cutting, or grazing). If peatlands were drained for agriculture, for example, then rewetting these ecosystems by increasing the peat water table depth close to the surface can significantly lower or even halt net carbon loss, as well as enable carbon sequestration (Günther et al. 2020; Mrotzek et al. 2020; Zerbe et al. 2013). Because drained peatlands will continue to emit CO_2, rewetting should occur as quickly as possible to maximize these climate benefits (Günther et al. 2020). Additionally, rewetting can reduce the risk of peat fires (FAO 2020). Limiting warming to 1.5°C, then, will require the restoration of 15 Mha of peatland—approximately a third of all degraded peatlands worldwide—by 2030 (Roe et al. 2021; Humpenöder et al. 2020). Although data are insufficient to assess global progress toward this target (Figure 48), available evidence suggests that current efforts to restore peatlands are occurring, but likely not at the speed and scale required (Andersen et al. 2017; BRGM 2021; Strack et al. 2022).

FIGURE 48 | Historical progress toward 2030 and 2050 targets for peatland restoration



Note: Mha = million hectares.

Sources: 2030 and 2050 targets adapted from Roe et al. (2021) and Humpenöder et al. (2020).

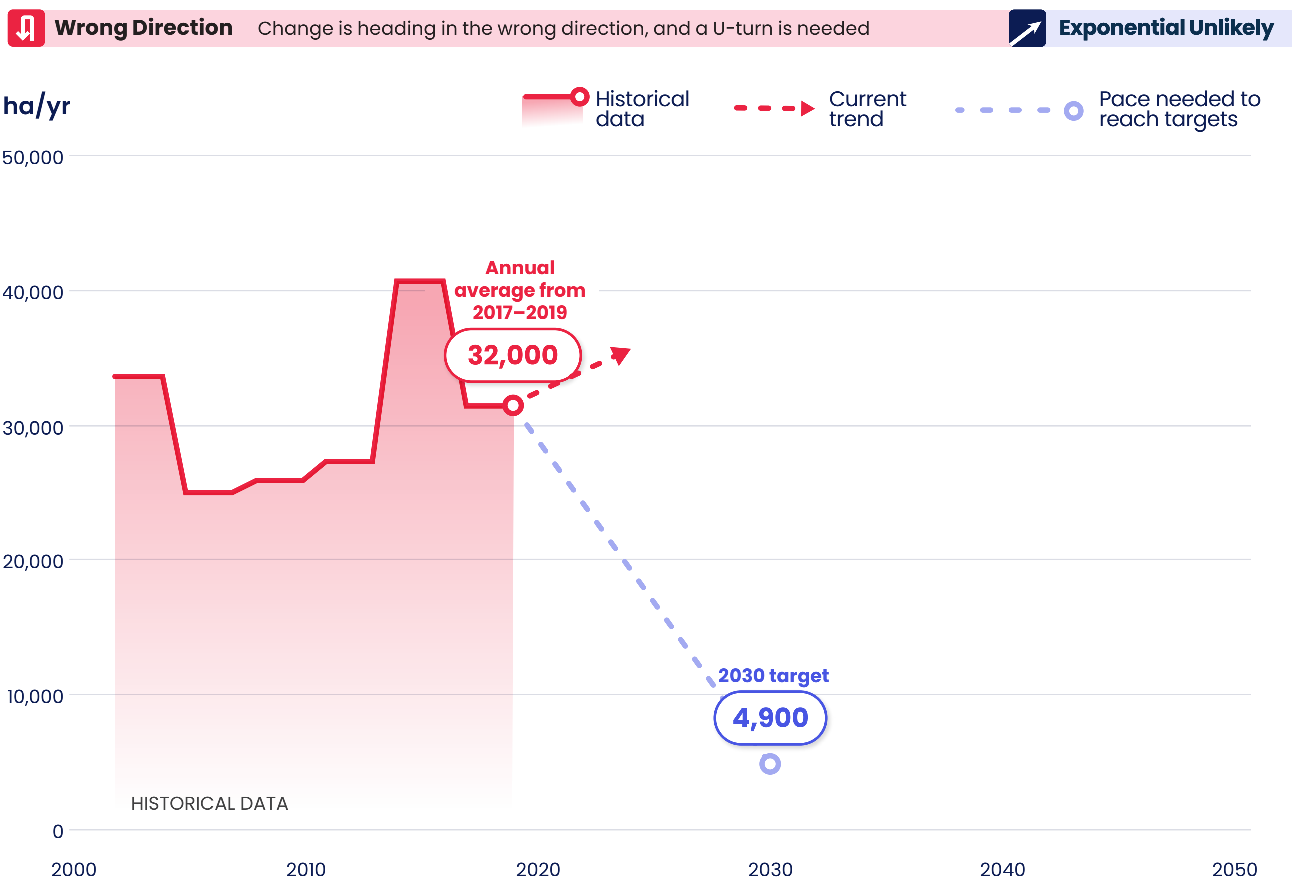
FORESTS AND LAND INDICATOR 5:
Mangrove loss (ha/yr)

- **Target**: The annual rate of gross mangrove loss globally declines to 4,900 ha/yr by 2030.[45]

Stretching across nearly 15 Mha of shoreline (Bunting et al. 2022), mangrove forests are global carbon hotspots, storing at least twice as much carbon per hectare as boreal, temperate, and tropical forests (Goldstein et al. 2020; Temmink et al. 2022).[46] But from 1999 to 2019, the world lost an estimated 0.56 Mha[47] of these coastal wetlands due to both natural and anthropogenic causes, with half of these losses attributable to direct human activities (e.g., conversion to aquaculture ponds) (Murray et al. 2022). Across Asia, this percentage increases significantly, with approximately 75 percent of gross mangrove losses attributable to direct human activities (Murray et al. 2022); Indonesia, which contains roughly 20 percent of the world's mangroves (Bunting et al. 2022), experienced the largest gross mangrove loss between 1999 and 2019 (Murray et al. 2022).

Although available estimates indicate that recent years have witnessed a rise in gross mangrove loss globally (Murray et al. 2022), it is important to note that these estimates include losses due to natural processes, as well as indirect anthropogenic causes like sea level rise, and some ongoing change is expected due to the dynamic nature of these ecosystems. When considering net change, global estimates indicate that net losses have been decreasing over the past two decades (Bunting et al. 2022), although they still outweigh gains globally (Murray et al. 2022; Bunting et al. 2022). Efforts to effectively halt gross mangrove loss, then, are heading in the wrong direction, and a step change in action is needed to reach the 2030 target (Figure 49).[48]

FIGURE 49 | 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 is used to calculate the linear trendline where possible. For this indicator, we calculated the trendline from 2010 to 2019. See Schumer et al. (2022) for more information.

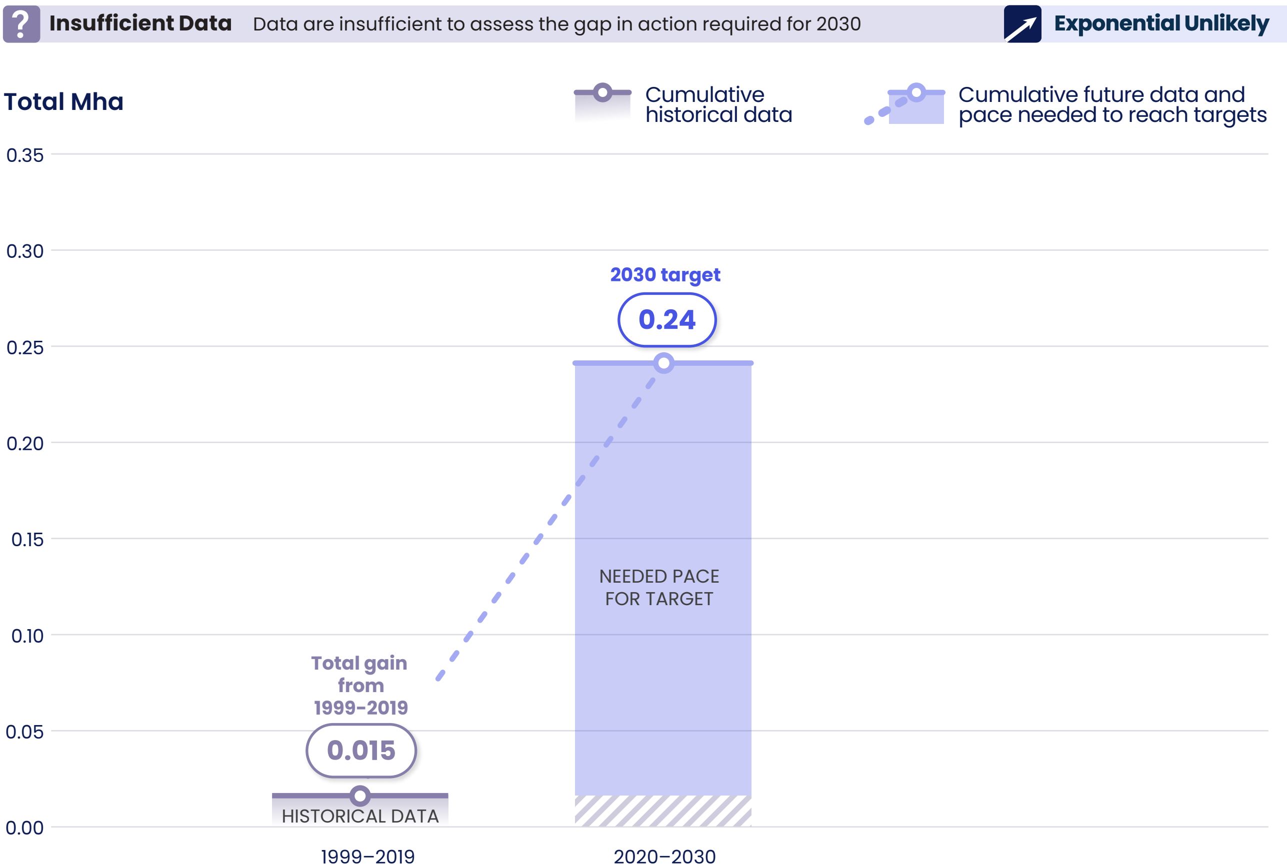
Sources: Historical data from Murray et al. (2022), which estimated mangrove loss for six three-year epochs. To estimate the average annual loss rate from 2010 to 2019, gross loss was divided by the number of years in each epoch. 2030 target from Roe et al. (2021).

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

- **Target**: Worldwide, mangrove restoration occurs across a total of 0.24 Mha by 2030.[49]

Restoring mangrove forests not only enhances their ability to sequester carbon but also may reduce GHGs that they otherwise would have continued to release for decades after certain disturbances (e.g., drainage for aquaculture ponds) (Pendleton et al. 2012; Temmink et al. 2022). Monitoring mangrove restoration, however, remains challenging. These coastal wetlands are naturally dynamic ecosystems, with changes also occurring due to broad-scale processes that can be influenced indirectly by human activities in adjacent watersheds, such as increased sedimentation, or exacerbated by the effects of climate change, such as increasing temperatures and sea level rise (Murray et al. 2022; Bunting et al. 2022; Spalding and Leal 2021). Global estimates indicate that only 8 percent of the approximately 0.18 Mha[50] of gross gain in mangrove extent from 1999 to 2019 can be attributed to direct human interventions, such as mangrove planting and restoration activities, with the vast majority of increases due to indirect drivers, such as the colonization of new sediments or inland migration (Murray et al. 2022). Due to these complex dynamics, data on the extent of gross mangrove gain are insufficient to assess progress toward this near-term mangrove restoration target (Figure 50).

FIGURE 50 | Historical progress toward 2030 target for mangrove restoration



Notes: Mha = million hectares. Murray et al. (2022) estimated that 0.18 Mha of gross mangrove gain occurred from 1999 to 2019, only 8 percent of which can be attributed to direct human activities, such as mangrove restoration. Accordingly, this report does not use gross mangrove gain to approximate mangrove restoration. We estimate the most recent data point for mangrove restoration by taking 8% of the total gross mangrove gain from 1999-2019. See Schumer et al. (2022) for more information.

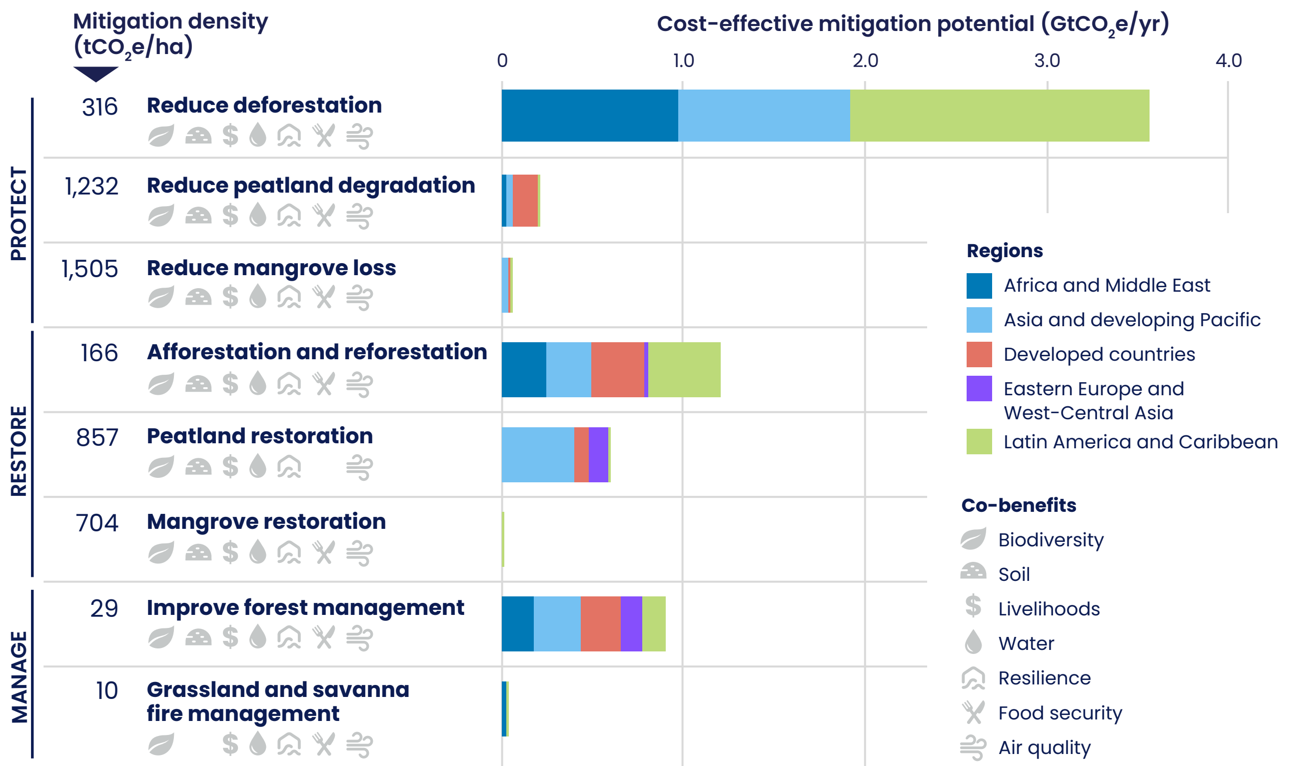
Sources: Historical data from Murray et al. (2022); 2030 target from Roe et al. (2021).

Global assessment of progress for forests and land

Protecting forests, peatlands, and mangroves yields multiple benefits for the climate by preventing the release of their large carbon stores, as well as by maintaining their ability to sequester carbon (IPCC 2022b) and, for tropical forests in particular, biophysical mechanisms that help cool the planet, such as evapotranspiration (Lawrence et al. 2022). Accordingly, effectively halting deforestation, peatland degradation, and mangrove loss delivers the lion's share—nearly 60 percent—of the cost-effective mitigation potential that land-based measures across these three ecosystems can contribute to holding global warming to 1.5°C (Figure 51) (Roe et al. 2021).[51] Safeguarding these ecosystems, which collectively hold roughly 1,020 gigatonnes of carbon, will also prove critical to near-term climate action, as they can lose carbon rapidly after certain disturbances, such as when large-scale commodity producers use fire to clear forested peatlands (Goldstein et al. 2020; Cook-Patton et al. 2021). Once released, much of this carbon is irrecoverable on policy-relevant timescales, effectively creating a permanent deficit in the world's remaining carbon budget for a 1.5°C future. It would take forests 6 to 10 decades to rebuild these lost carbon stocks, well over a century for mangroves, and many centuries to millennia for peatlands (Goldstein et al. 2020; Temmink et al. 2022).

Yet recent efforts to protect these high-carbon ecosystems remain largely inadequate. Although permanent forest losses fell by 2 percent from 2020 to 2021, these rates are not declining fast enough to hold global warming to 1.5°C. From 2015 to 2021, deforestation occurred across an area roughly the size of Iraq (45 Mha total), emitting a total of 25 $GtCO_2e$, and nearly half of these permanent losses (22 Mha) happened in humid tropical primary forests (Hansen et al. 2013; Curtis et al. 2018; Tyukavina et al. 2022; Turubanova et al. 2018; Harris et al. 2021), which are among the world's most important landscapes for carbon storage and biodiversity (Harris et al. 2021; Mackey et al. 2020; Gibson et al. 2011). Should deforestation continue unabated, these ecosystems risk becoming net sources of GHG emissions and catalyzing feedbacks that could amplify global warming. Already, deforested regions across southeastern Amazonia release more carbon than they store (Gatti et al. 2021), and some scientists estimate that deforesting just 20 percent of the Amazon basin could push it past a tipping point (with several finding that the world has lost 17 percent of this forest since 1970), jump-starting a cas-

FIGURE 51 | 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.
Source: Roe et al. (2021).

cade of events that could transform the world's largest humid tropical primary forest into a savanna (Lovejoy and Nobre 2019; Lenton 2020). Such large-scale dieback of the Amazon could release over 90 $GtCO_2$ into the atmosphere (Steffen et al. 2018), as well as trigger shifts in biophysical mechanisms that would also contribute to global warming (Lawrence et al. 2022).

Peatlands and mangrove forests, both global hotspots for carbon sequestration and long-term carbon storage (Temmink et al. 2022), have also suffered losses in recent years. Although they slowed dramatically from an estimated 1–2 percent per year in the late 20th century (Friess et al. 2019) to just 0.13 percent per year from 2000 to 2016 (Goldberg et al. 2020), average annual rates of gross global mangrove loss are once again ticking upward, such that a step change in action is now needed to help limit global warming to 1.5°C (Murray et al. 2022). Similarly, although data on peatland degradation, specifically, are limited, data on drained organic soils, which include but are not limited to peat soils, suggest that degradation of the world's peatlands continued in recent decades. From 1990 to 2019, for example, the area of drained organic soils steadily increased across Africa and Asia. Southeast Asia, in particular, experienced an acceleration in these trends, driven largely by palm oil cultivation across tropical peatlands (Conchedda and Tubiello 2020), and Indonesia and Malaysia, which collectively hold the vast majority of the region's peatlands (Page et al. 2011; Xu et al. 2018), lost peat swamp forest cover across an area roughly the size of Costa Rica (5.4 Mha) from 1990 to 2010 (Miettinen et al. 2012). The conversion and degradation of these two ecosystems risk releasing large soil carbon stocks accumulated over centuries to millennia into the atmosphere. Once disturbed (e.g., construction of aquaculture ponds or drainage for agriculture), both can continue emitting GHGs for decades to centuries, with mangroves emitting a relatively high proportion of their carbon stores rapidly after land-use change and peatlands releasing their significantly larger carbon stores over a much longer time period (Temmink et al. 2022).

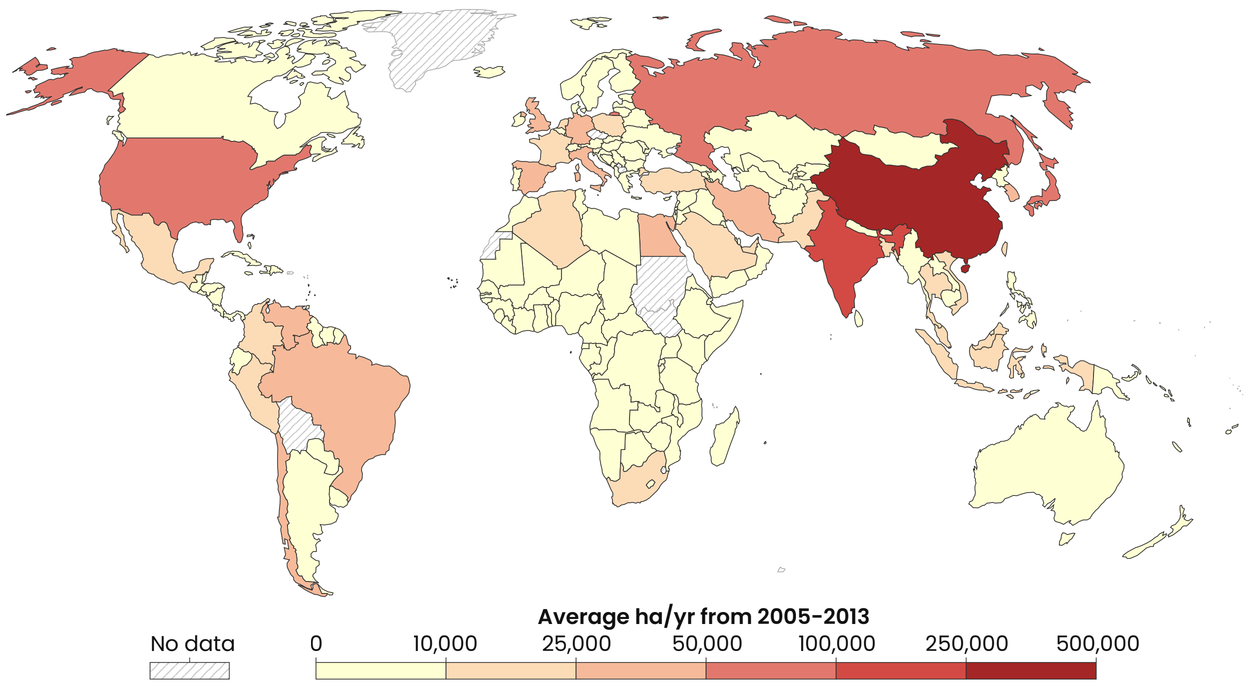
Although protecting forests, peatlands, and mangroves should be prioritized (Cook-Patton et al. 2021), achieving the Paris Agreement's 1.5°C temperature goal also will require large-scale restoration (IPCC 2022b). And while restoration is more expensive and it can take decades (if not longer) for these ecosystems to regain ecological functions (Sasmito et al. 2019; Poorter et al. 2021; Kreyling et al. 2021; Su et al. 2021; Cook-Patton et al. 2021), regenerating forests, peatlands, and mangroves can still deliver about 30 percent of the cost-effective mitigation potential that land-based measures across these ecosystems can contribute to hold global warming to 1.5°C (Figure 51) (Roe et al. 2021). Reforesting 300 Mha, an area roughly the size of India, by 2050 can sequester about 1.2 $GtCO_2$ annually (Roe et al. 2021). Although restoring peatlands and mangroves will make smaller contributions to limiting global temperature rise to 1.5°C (a combined 0.6 $GtCO_2$ per year at up to \$100/tCO_2e),[52] these activities have among the highest mitigation densities of all land-based measures and, in some countries, particularly across the tropics, can play an outsized role in delivering national climate targets (Roe et al. 2021). However, achieving these carbon sequestration rates, as well as avoiding further GHG emissions from degraded peatlands, by 2050 will require recent restoration efforts to accelerate significantly over this decade. Global progress made in reaching near-term targets remains off track for reforestation, and although data are insufficient to assess change made toward peatland and mangrove restoration targets, available evidence indicates that current efforts, while ongoing, also remain insufficient (Murray et al. 2022; Strack et al. 2022; Andersen et al. 2017; BRGM 2021).

Across all three ecosystems, large-scale commodity production continues to be the primary driver of land-use change and degradation, as well as a significant barrier to restoration. Agricultural expansion, mining, and oil and gas extraction, for example, accounted for over 80 percent of deforestation from 2001 to 2021 (WRI 2022c; Curtis et al. 2018; Hansen et al. 2013; Turubanova et al. 2018; Tyukavina et al. 2022), while rice, shrimp, and palm oil cultivation spurred nearly 50 percent of mangrove losses from 2000 to 2016 (Goldberg et al. 2020). Similarly, conversion to industrial plantations, logging, and agricultural practices (e.g., using fire to clear land and constructing drainage canals to enable cultivation) are primarily responsible for tropical peatland degradation (Dohong et al. 2017).

Much of the demand for these commodities originates in the world's wealthiest countries. Between 29 and 39 percent of GHG emissions from deforestation, for example, were embodied in internationally traded commodities from 2010 to 2014 (Pendrill et al. 2019b), with developed countries and emerging economies importing an increasingly large share of deforestation embodied in commodities (Figure 52) (Pendrill et al. 2019a). Consumption patterns across G7 countries alone drive annual losses averaging 3.9 trees per person (Hoang and Kanemoto 2021). As the global population grows and incomes rise, demand for food, feed, fiber, and fuel will likely increase, intensifying these pressures on forests, peatlands, and mangroves (Haberl et al. 2014; Searchinger et al. 2019b). Such pressures not only spur additional conversion and degradation but also disincentivize restoration, such that the economic gains of producing commodities far outweigh the benefits of restoring ecosystems (Hanson et al. 2015; Ding et al. 2017; Chaturvedi et al. 2019). Preventing commodity-driven losses and degradation, as well as retiring agricultural fields for restoration, while achieving food security for all, will depend on demand-side shifts, particularly dietary changes in developed countries (Food Indicator 6) and global reductions in food loss and waste (Food Indicators 4 and 5). Sustainably producing more food, feed, and fiber on existing agricultural lands (Food Indicators 2 and 3) to feed 10 billion people by 2050, while minimizing or eliminating harmful environmental impacts will also be required (Searchinger et al. 2019b).

Climate change poses another potential threat to forests, peatlands, and mangroves. Rising atmospheric concentrations of CO_2 over the last six decades have increased the global ocean and land carbon sinks,[53] which will likely continue to grow throughout this century. However, should the world follow a high-emissions pathway, the proportion of atmospheric CO_2 that these sinks can absorb will likely decline, and future disturbances, including climate impacts, may spur further decreases (IPCC 2021). Warmer temperatures coupled with longer, more frequent, and severe droughts may limit terrestrial ecosystems' carbon uptake, while recurrent, more extreme wildfires may release carbon stored in forests and peatlands back into the atmosphere, as well as emit other GHGs like methane (IPCC 2022a). Similarly, rising sea levels and extreme weather events, which already help drive mangrove losses globally (Goldberg et al. 2020), may accelerate declines in these coastal forests (IPCC 2022a). As carbon losses stemming from the conversion and degradation of these ecosystems increase, so too does the risk of triggering self-reinforcing feedbacks that could both amplify warming and spur further losses across the world's forests, peatlands, and mangroves (IPCC 2022a). However, both the timing

FIGURE 52 | Deforestation embodied in imported commodities



Note: ha/yr = hectares per year.
Source: Pendrill et al. (2019a).

and magnitude of these feedbacks, as well as the potential tipping points for carbon losses across these ecosystems, remain largely uncertain (IPCC 2021, 2022a).

Well-designed, appropriately implemented measures to protect and restore forests, peatlands, and mangroves can not only help mitigate climate change, thereby reducing the risks of catalyzing feedbacks that could amplify warming, but also deliver significant benefits for adaptation, sustainable development, and biodiversity. Intact, healthy forests, for instance, filter out air pollutants, provide food, and support livelihoods, while peatlands help maintain water quality, absorb flood waters, and harbor rare and endangered species (Joosten 2021; Seymour and Busch 2016). Similarly, mangroves also protect shorelines from erosion, safeguard coastal communities from sea level rise and storm surges, and provide nursery grounds for fisheries (Jakovac et al. 2020). Globally, these ecosystem services generate annual benefits worth an estimated $3,800 per hectare for forests and about $140,000 per hectare for wetlands (Costanza et al. 2014).

Ensuring that land-based mitigation measures across these ecosystems deliver these local benefits, as well as global carbon sequestration and storage services, is critical to long-term success, and, to that end, so too is meaningfully engaging Indigenous Peoples and local communities living within or nearby forests, peatlands, and mangroves as full partners in the design, implementation, and monitoring of such projects (Höhl et al. 2020). Done well, inclusive, participatory decision-making processes allow communities to shape projects' goals to ensure that they deliver benefits that community members prioritize (e.g., improving human health or protecting culturally significant sites), that they are tailored to specific contexts, and that they avoid exacerbating existing inequalities (e.g., by providing alternative livelihoods where needed). In turn, these processes can boost local support for conservation projects 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 passed legislation in 1993 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), and 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).

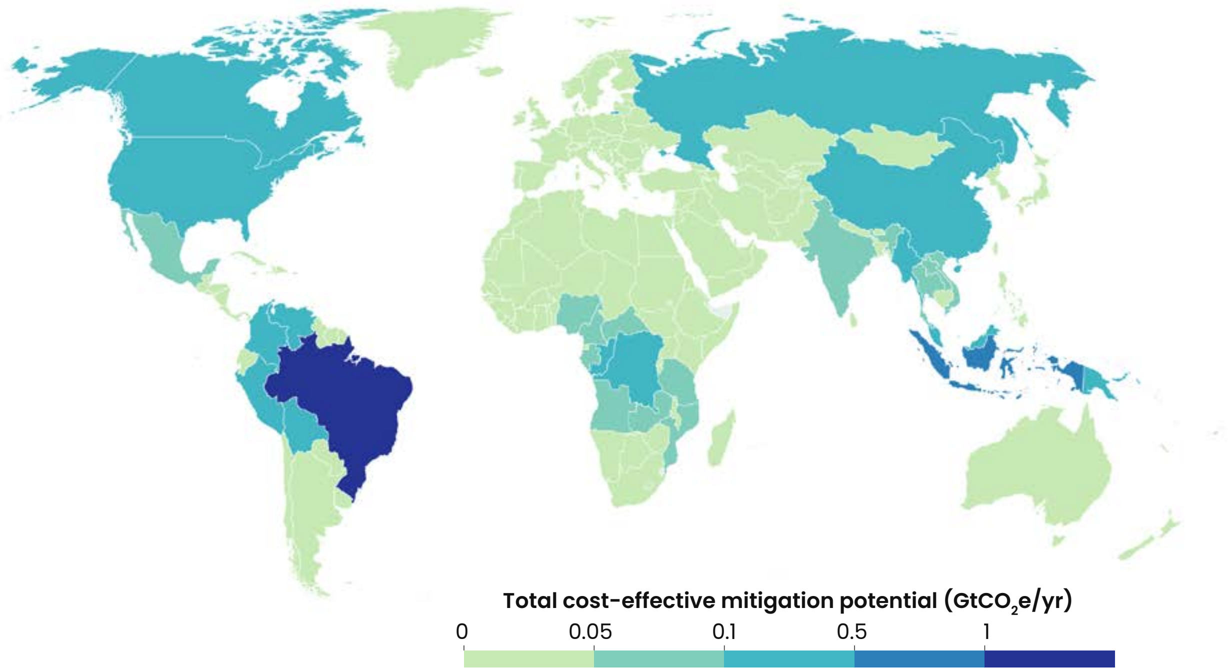
Indigenous and local communities, however, are not monoliths, and it is critical that decision-making processes account for existing inequities between and within them. Women, for example, often face barriers to influencing land governance, ranging from gendered divisions of labor that assign much of the unpaid, caregiving responsibilities to women, 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, existing 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 shape, as well as benefit from, forest restoration (Buckingham and Ellersick 2015).

Not only must land-based mitigation measures deliver benefits locally and globally, but they also must strive to avoid unintended environmental consequences. Planting nonnative species and/or monocultures, for example, can harm biodiversity and threaten ecosystem services, while reforestation at higher latitudes, although beneficial for conserving biodiversity, has limited climate mitigation benefits, as doing so can create a net warming effect by altering the reflectivity of the planet's surface (IPCC 2022b). Across Southeast Asia, for example, shortsighted mangrove restoration projects focused solely on large-scale tree planting have too often relied on a single, sometimes alien species, and a survey of these initiatives across 11 countries found very few trees survived 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), while overreliance on alien mangrove species spurred losses in ecosystem functions across China (Lee et al. 2019). But when broader landscape restoration principles are applied (e.g., by focusing on restoring entire landscapes, recovering ecological functions, delivering multiple benefits, etc.), these harmful impacts can be avoided. For example, reestablishing natural hydrological regimes across mangrove forests is often more successful in restoring these coastal ecosystems than planting saplings, alone (Lewis 2001).

Enabling conditions for climate action across forests and land

Commitments to conserve forests, peatlands, and mangroves, among other ecosystems, have risen dramatically in recent years. Nearly 75 countries, states, and associations pledged to help restore 350 Mha of deforested and degraded landscapes by 2030 under the Bonn Challenge (IUCN 2020), which includes regional

FIGURE 53 | Global distribution of cost-effective mitigation potential for forests, peatlands, mangroves, and grasslands by country



Note: $GtCO_2e$/yr = gigatonnes of carbon dioxide equivalent per year.
Source: Roe et al. (2021).

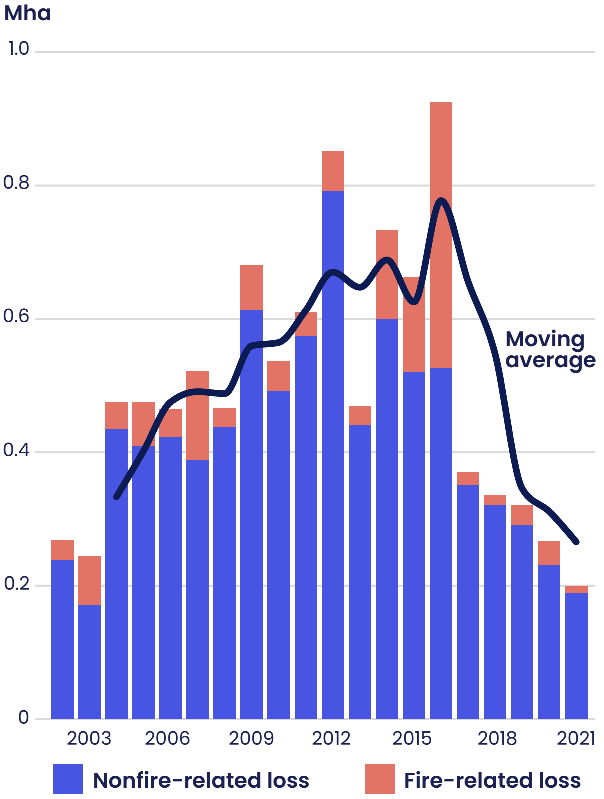
efforts like the African Forest Landscape Restoration Initiative and Latin America's Initiative 20 × 20. More than 200 governments, companies, civil society organizations, and associations representing Indigenous Peoples and local communities endorsed the New York Declaration on Forests, committing to end natural forest loss by 2030 (NYDF Assessment Partners 2021). And at COP26, over 140 countries signed the Glasgow Leaders' Declaration on Forests and Land Use (2021), agreeing to halt and reverse forest loss and land degradation within the next decade.

Yet efforts to translate these multilateral commitments into effective actions have fallen short, with leaders missing interim targets under the Bonn Challenge and the New York Declaration on Forests. Substantial barriers to implementation also persist, including weak or conflicting policies, fragmented governance, limited institutional capacity, corruption, complex land tenure regimes, misaligned and insufficient finance, and growing demand for commodities that drive tropical deforestation and degradation. Some of these challenges are especially acute across developing countries, which hold 85 percent of the world's cost-effective mitigation potential for protecting, restoring, and sustainably managing high-carbon ecosystems (Figure 53) (Roe et al. 2021). However, given that internationally traded commodities embody a significant amount of deforestation (Pendrill et al. 2019a; Hoang and Kanemoto 2021), financial institutions, companies, and consumer country governments also share responsibility for achieving 1.5°C-aligned targets for land-based mitigation. While the factors that enable climate action across these ecosystems vary by context, the following measures can help surmount current obstacles.

Strengthen national conservation policies

Effectively conserving high-carbon ecosystems will require countries to strengthen their policies by placing moratoria on conversion, establishing and expanding protected areas,[54] financially incentivizing conservation (e.g., through payment for ecosystem services schemes), encouraging community forest management, and legally recognizing Indigenous Peoples' land rights, among other measures (Chaturvedi et al. 2019; NYDF Assessment Partners 2021; Wolf et al. 2021; IPCC 2022b). Following devastating fires in 2015, Indonesia, for example, strengthened regulations to limit peatland drainage across commercial plantations in 2016, issued a moratorium on new palm oil concessions in 2018, and made another nationwide moratorium on new concessions in primary forests and peatlands permanent in 2019 (Budiman et al. 2021; NYDF Assessment Partners 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; WRI 2022d; Mursyid et al. 2021). Together, these actions have contributed to declines in primary forest loss since 2017 (Figure 54), as well as the restoration of

FIGURE 54 | Humid tropical primary forest loss across Indonesia



Notes: Mha = millions of hectares. Much of Indonesia's 2016 fire-related forest loss figure was actually due to burning in 2015. Burned areas were detected late because of insufficient clear Landsat images at year's end (the same is also true to a lesser extent for 2019 and 2020). The three-year moving average, then, may offer a more relevant picture of trends due to uncertainty in the year-to-year comparisons.

Sources: Weisse and Goldman (2022), based on Hansen et al. (2013), Turubanova et al. (2018), and Tyukavina et al. (2022).

nearly 35,000 hectares of mangroves and 300,000 hectares of peatlands in 2021 alone (Weisse and Goldman 2022; BRGM 2021).

When effectively implemented, these policies can also bolster voluntary corporate action to reduce deforestation (Alves-Pinto et al. 2015; Lambin et al. 2018; Taylor and Streck 2018; Carodenuto 2019; Garrett et al. 2019; Furumo and Lambin 2020). For example, government actions to improve forest monitoring, establish conservation areas, legally recognize Indigenous Peoples' land rights, impose penalties for deforestation, strengthen enforcement of deforestation restrictions, and suspend agriculture credit access in communities with disproportionately high deforestation rates contributed to the success of the industry-led soy moratorium across the Brazilian Amazon between 2004 and 2012 (Nepstad et al. 2014; Heilmayr et al. 2020). Recent studies, however, have shown that this moratorium may have displaced some deforestation to nearby grasslands, another important ecosystem for carbon storage (Conant et al. 2017), underscoring the importance of broadening the geographic scope of corporate actions and supportive public policies (IPCC 2022b).

While many developed countries have established similarly strong environmental laws within their borders, adoption of such legal frameworks varies significantly across developing countries, where the pressure to address socioeconomic challenges, stemming largely from historical and ongoing patterns of inequity like colonialism, has led some governments to pursue development strategies that harm high-carbon ecosystems instead (or in spite) of regulations to conserve them (IPCC 2022b; NYDF Assessment Partners 2021). And even where gains have been made, such as in Indonesia and Brazil, they remain fragile. Home to the world's largest tropical forests, Brazil, Colombia, the Democratic Republic of the Congo, Indonesia, and Peru have all rolled back environmental laws and regulations, weakened safeguards, and cut the budgets of agencies tasked with enforcing conservation policies during the COVID-19 pandemic (NYDF Assessment Partners 2021). Many of these policy reversals were already well underway in Brazil, where political will to conserve forests has evaporated and deforestation is now rising (Seymour 2021; NYDF Assessment Partners 2021).

Improve national and subnational governance to step up enforcement

Good governance[55] is foundational to achieving international commitments and implementing national policies (IPCC 2022b). Yet, in 2020, nearly 100 countries containing roughly 75 percent of global cost-effective mitigation potential for land-based measures ranked in the bottom half of nations on at least two out of three critical dimensions of governance: rule of law,[56] government effectiveness,[57] and control of corruption[58] (Kaufmann and Kraay 2020; Roe et al. 2021). While some developing countries grapple with resource constraints that weaken institutional capacity to enforce environmental laws and halt illegal activities, others struggle with corruption, whereby officials allocate land for political gain (FAO and UNEP 2020; Kaufmann and Kraay 2020; Roe et al. 2021; Transparency International 2021; NYDF Assessment Partners 2021; IPCC 2022b). Consequently, nearly 70 percent of tropical forest loss driven by commercial agriculture was illegal from 2013 to 2019—representing a 28 percent increase in illegal deforestation compared to 2000 to 2012 (Dummett et al. 2021). There is no silver bullet to strengthening governance. For some countries, access to finance, capacity-building, and technology transfer may help officials overcome resource constraints, while for others wrestling with corruption, a wider range of reforms may be needed, including those that strengthen transparency, accountability, and the rule of law.

Enhance policy coherence

Conservation policies in both producer and consumer countries are often undercut by those that incentivize development, particularly agricultural expansion, across high-carbon ecosystems (Friess et al. 2016; Evers et al. 2017; Herr et al. 2017; Bastos Lima et al. 2017; Dohong et al. 2018; Friess et al. 2019; Ekawati et al. 2019; Budiman et al. 2021; Pham et al. 2022). Until recently, for example, Norway signed agreements promising to deliver results-based payments to tropical countries that reduced deforestation, as the government's pension fund—the world's largest sovereign wealth fund, currently valued at over $1 trillion—invested in companies responsible for commodity-driven deforestation (Taylor 2019). Similarly, in Ecuador, the government simultaneously sought to reduce emissions from deforestation, in part, by offering direct payments to landowners for conserving forests, while also channeling funding through the Ministry of Agriculture to expand oil palm production, a primary driver of deforestation across the country (Bastos Lima et al. 2017).

While consumer countries can focus on reducing inconsistencies in trade, public investment, and foreign aid policies, among others, agricultural ministries in producer countries can improve coherence by adopting complementary, land-sparing measures that sustainably boost yields to help relieve competing pressures on ecosystems and free farmland for restoration (Hanson et al. 2015; Chaturvedi et al. 2019). Observations from multiple countries, alongside modeling studies, suggest that minimizing agricultural expansion both through demand-side shifts (Food Indicators 4–6) and by linking yield gains with ecosystem protection has the greatest potential to protect aboveground, land-based carbon stocks, while also feeding a growing population (Williams et al. 2018). Governments can help farmers sustainably produce more food on less land and lower GHG emissions by, for example, investing in crop breeding (e.g., speeding up breeding cycles in developing countries or focusing breeding improvements on orphan crops), incentivizing adoption of new livestock feeds to reduce methane emissions intensities and boost productivity, and encouraging improvements in soil and water management practices (e.g., fertilizer microdosing or rainwater harvesting) (Searchinger et al. 2019b). Similarly, urban planning practices that encourage coastal retreat, such as setbacks or the transfer of development rights from shoreline areas to inland zones, can help reduce competition for coastlines, as well as enable mangrove restoration and inward migration (Leo et al. 2019), one process by which these wetlands adapt to sea level rise (Schuerch et al. 2018). To conserve all high-carbon ecosystems, however, policies must go beyond reducing direct habitat conversion to addressing the underlying drivers of loss and degradation—for mangroves, for example, this includes sea level rise, pollution, shoreline hardening (e.g., building seawalls), and declining sediment due to dammed rivers (Friess et al. 2019; Goldberg et al. 2020; IPCC 2022a). Otherwise, even highly protected areas may still suffer significant degradation.

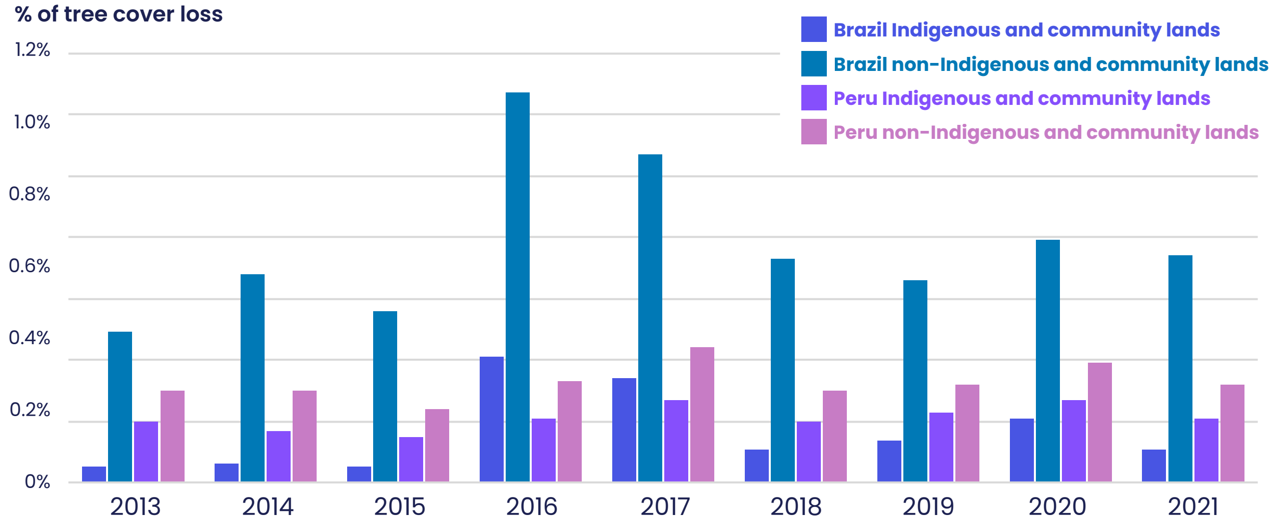
Policy incoherence is often accompanied by complex, fragmented governance, both of which impede implementation of land-based mitigation measures (Friess et al. 2016; Rotich et al. 2016; Evers et al. 2017; Chaturvedi et al. 2019; Budiman et al. 2021; Khan and Giessen 2021; NYDF Assessment Partners 2021). Officials advancing different mandates across agencies and decision-making levels can create confusion, paralysis, or even conflict—all of which undermine policy implementation. These challenges are especially acute for mangroves, which sit at the intersection of land and sea. In Indonesia, for example, at least five national institutions with competing interests have authority over the country's mangroves (Arifanti 2020), while the responsibility for implementing policies may also rest with subnational governments. Such complexity has frustrated conservation efforts, although the tide may be turning as Indonesia develops an overarching national mangrove management strategy (Arifanti 2020; Mursyid et al. 2021). Additional options to overcome fragmentation include integrated land-use planning, integrated coastal zone management planning, interagency taskforces to strengthen coordination, and jurisdictional approaches (Chaturvedi et al. 2019).

Clarify, secure, and uphold land rights

Insecure, unclear tenure, including the erosion of customary tenure regimes, heightens vulnerability to land grabbing, speculation, and disputes that spur not only ecosystem loss but also violence that threatens communities' well-being (Azevedo-Ramos and Moutinho 2018; Reydon et al. 2020; Rodríguez-de-Francisco et al. 2021; Lim et al. 2017; Gaveau et al. 2017; Barrow et al. 2016; Oyono 2021; Global Witness 2021). Across the Brazilian Amazon, for example, 50 Mha of public forests (an area roughly the size of Spain) lack an assigned tenure status. From 1997 to 2018, deforestation occurred across 2.6 Mha of these undesignated lands, emitting 1.2 $GtCO_2$, while about another 12 Mha were registered illegally as private property (Azevedo-Ramos et al. 2020). Similarly, in Indonesia, burning peatlands across abandoned logging concessions with uncertain tenure offers smallholder farmers a clear pathway to land ownership (Purnomo et al. 2019).

Strengthening Indigenous Peoples' forest and land rights offers one 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

FIGURE 55 | Percent tree cover loss inside and outside of Indigenous and community lands in Peru and Brazil



Notes: Between 2013 and 2021, the percentage of tree cover loss outside of Indigenous and community lands in Brazil and Peru (two forested countries with publicly available official community land maps) was higher than within them. Loss proportion by year is based on the hectares of loss inside Indigenous and community lands and outside of these lands, divided by the tree cover extent in 2010 as defined by Hansen et al. (2013). This proportion is then multiplied by 100 to get a percentage. Indigenous and community lands are defined using LandMark Map (2021). Tree cover loss is defined using the Hansen et al. (2013) tree cover loss dataset.

Source: WRI (2022e).

than in nearby forests (e.g., see Figure 55), 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). Securing Indigenous Peoples' land tenure through various reforms, such as titling and legally recognizing lands, can help enable these communities to protect their forests from emerging threats, but only if governments uphold these rights in practice (Stevens et al. 2014; Blackman et al. 2017; Blackman and Veit 2018; Baragwanath and Bayi 2020). Too often, they do not (FAO and FILAC 2021; UNDESA 2021). Similarly, recent evidence shows that improving local communities' land rights through community forestry management programs, such as Indonesia's Hutan Desa (Village Forest) scheme (Santika et al. 2019), can also help reduce deforestation (IPCC 2022b).

Secure tenure regimes also underpin successful restoration. Communities need assurances that they will accrue the benefits of reestablishing trees, rewetting peatlands, or restoring tidal regimes across 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 global progress in strengthening tenure security remains insufficient. Nearly 1 billion people believe that they could lose part of their land or the right to use it within five years (Feyertag et al. 2020). In nations containing roughly 55 percent of the world's cost-effective mitigation potential for restoration, perceived tenure insecurity is above the global average (Roe et al. 2021; Feyertag et al. 2020).

Align public and private finance with global efforts to conserve forests, peatlands, and mangroves

Many land-based mitigation measures are widely available, readily deployable, and inexpensive—actions that cost less than \$20/tCO_2e can deliver 30–50 percent of AFOLU's mitigation potential (IPCC 2022b). Yet public and private finance lags far behind need. Although total tracked climate finance earmarked for mitigation in this system has risen since 2013 (Buchner et al. 2021; Macquarie et al. 2020; Oliver et al. 2018; Mazza et al. 2016), the IPCC estimates that, to hold global warming to below 2°C, recent mitigation investments in AFOLU must increase rapidly—by a factor of 10 to 29 by 2030 (see Finance Indicators 1–3) (IPCC 2022b).

To date, initiatives to reduce emissions from deforestation and degradation (REDD+)[59] have received the lion's share of climate finance for AFOLU (IPCC 2022b). Since its international debut, REDD+ has garnered attention as an innovative framework through which developing countries can receive ex-post payments for verified GHG emissions reductions financed through either public funds or carbon markets (Seymour and Busch 2016). To qualify for this results-based finance, more than 50 developing countries have established national REDD+ strategies and committed $10.1 billion in domestic finance to activities under these plans (NYDF Assessment Partners 2021). Yet international REDD+ finance has yet to fully materialize. Just over half of pledged funding for REDD+ readiness and implementation has been disbursed since 2010, while roughly half of committed results-based payments have been issued. In 2021, for example, the Indonesian government ended its REDD+ agreement, citing a "lack of concrete progress" in receiving payments for results achieved in 2016 and 2017 (NYDF Assessment Partners 2021).

Restoration finance also remains scarce, particularly in developing countries where public revenues for such initiatives are often confined to environmental ministries' relatively small budgets (Ding et al. 2017). These nations often struggle with chronic debt, low credit ratings, and financial burdens from COVID-19—challenges that make it difficult for them to raise private capital for, as well as allocate limited public funds to, all mitigation activities, including restoration (IPCC 2022b). Investors' tendency to channel greater shares of capital into their own countries,[60] coupled with perceptions of land-based mitigation initiatives, and especially restoration, as too risky (e.g., limited returns and long time horizons), pose additional hurdles to scaling up private finance (Ding et al. 2017; IPCC 2022b).

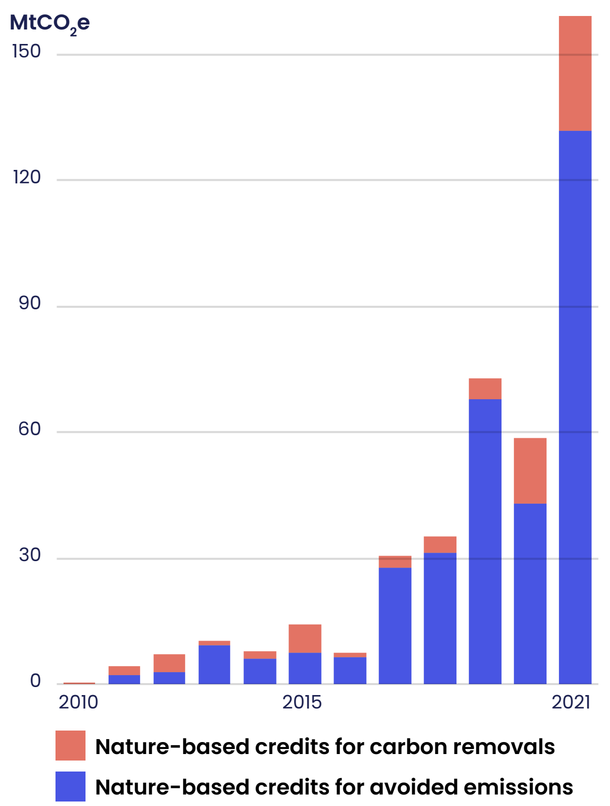
Worse still, efforts to align broader financial flows across AFOLU with 1.5°C pathways remain insufficient (NYDF Assessment Partners 2021). Just 5 percent of agricultural subsidies, recently valued at $600 billion per year,[61] support conservation or climate objectives (Searchinger et al. 2020), and many still incentivize perverse actions (e.g., the European Union's payments to drainage-based peatland agriculture) (Tanneberger et al. 2021). Additionally, the world's leading financial institutions continue to channel some $5.5 trillion to 350 companies with the highest exposure to deforestation risks across their supply chains (Forest 500 2022b).

Recent announcements suggest that the tide may be starting to turn. At COP26, over 30 financial institutions managing more than $8.7 trillion in assets committed to eliminating agricultural commodity-driven deforestation risks from their investments and lending portfolios by 2025 (Race to Zero 2021b). Governments also pledged $12 billion in support of the Glasgow Leaders' Declaration on Forests and Land Use, while private sector leaders promised to deliver another $7.2 billion (Prime Minister's Office 2021). Referencing this declaration, governments and philanthropies committed $1.7 billion to advance the forest tenure rights of Indigenous Peoples and local communities ("COP26 IPLC Forest Tenure Joint Donor Statement" 2021).

Nature-based credits traded in voluntary carbon markets represent another rapidly growing source of much-needed finance for land-based mitigation measures across high-carbon ecosystems (IIF 2021), and demand for these credits has soared in recent years (Figure 56), particularly among companies (Climate Focus 2022). But such growth with guardrails also risks undermining climate action (Steer and Hanson 2021)—for example, if those purchasing nature-based credits as offsets use them to delay their own emissions reductions. Some organizations are proposing that companies purchase nature-based credits as financial contributions to climate mitigation, in addition to rapidly lowering emissions, as these credits cannot compensate for GHGs released elsewhere (Day et al. 2022).

Although promising, these commitments and carbon credits will need to materialize quickly, and all still fall short of the over $400 billion needed per year for forests alone by 2050 (IPCC 2022b). Additional strategies to increase public finance include adopting economy-wide carbon pricing schemes (see Finance Indicator 5), conditioning agricultural subsidies (e.g., farm payments) on the protection of ecosystems, integrating

FIGURE 56 | Nature-based carbon credits issued



Notes: $MtCO_2e$ = million tonnes of carbon dioxide equivalent. Data include carbon credits issued by the four leading standards, Verra's Verified Carbon Standard, the Gold Standard's SustainCert, American Carbon Registry, and Climate Action Reserve.

Source: Climate Focus (2022).

restoration costs into the budgets of better-funded ministries (e.g., agriculture), issuing green and/or blue bonds, and implementing well-designed debt-for-nature swaps (Searchinger et al. 2020; Ding et al. 2017; Essers et al. 2021; Sommer et al. 2020; Lütkehermöller et al. 2021; Sumaila et al. 2020). To scale up private finance, intermediary financial institutions can make smaller restoration projects more attractive to investors by bundling them together, while governments and philanthropies can de-risk private sector investments by adopting measures like first-loss capital structures, tax credits, or insurance guarantees for losses related to currency fluctuations or political instability, for example (Ding et al. 2017; Löfqvist and Ghazoul 2019). Increasing access to microfinance, smaller-scale grants, payment for ecosystem services schemes, and voluntary carbon markets can help these funds reach those charged with implementation (FAO and UNCCD 2015; Wylie et al. 2016).

Advance ecosystem mapping and monitoring

Improved monitoring can help policymakers better enforce conservation policies, assess interventions' effectiveness, and secure results-based payments. These tools can also enable financial institutions and companies to identify their exposure to deforestation risks, as well as allow civil society organizations to hold leaders accountable to their commitments to conserve forests, peatlands, and mangroves.

The last two decades have witnessed major advances in forest monitoring. Historically, governments relied on field-based approaches to track changes in forest extent—expensive, time-consuming, and labor-intensive processes that, at best, nations undertake every five years (Petersen et al. 2018). But now, public satellites provide freely available, medium-resolution imagery almost weekly, while a growing number of commercial satellite companies sell near-daily, higher-resolution imagery. Gains in computing power have enabled more effective processing of these data, and together these innovations have led to forest detection systems that automatically alert decision-makers to potential deforestation in near-real time (Finer et al. 2018). When coupled with trainings to build local capacity, this improved monitoring has helped reduce deforestation in the Peruvian Amazon (Slough et al. 2021), as well as across the Congo Basin (Moffette et al. 2021). Advances in tracking forest gains, however, trail those made in monitoring forest loss. Gradual increases in tree cover, for example, cannot be detected from satellite imagery on annual timescales, and gains outside forests also remain difficult to identify.

Still, these remote-sensing breakthroughs have benefited mangrove forest monitoring (Giri et al. 2011; Hamilton and Casey 2016; Worthington et al. 2020), with near-annual data on gains and losses now publicly available (Bunting et al. 2022). To support rapid responses to emerging threats, particularly in countries that lack the resources to process and manage remotely sensed data, Global Mangrove Watch is piloting an alert system that provides monthly disturbance notifications across Africa (Spalding and Leal 2021).

Although these advances in remote sensing can also provide data needed to monitor the world's peatlands (Czapiewski and Szumińska 2021), progress made in mapping, let alone monitoring, these wetlands also lags far behind forests. The most comprehensive global peatland map, for example, combines global, regional, and national data from geological surveys, soil maps, and wetland databases produced between 1990 and 2013 (Xu et al. 2018), but many of the world's most peat-rich countries lack complete or up-to-date national surveys of this ecosystem. The Democratic Republic of the Congo and Indonesia, for example, have yet to develop accurate countrywide peatland maps (although efforts are underway in both countries), while the United Kingdom still relies on field surveys, many of which were conducted three or more decades ago (FAO 2020). This disparity between forests and peatlands underscores the challenges of mapping this ecosystem. In addition to the medium-resolution satellite imagery used to measure forest extent, higher-resolution, remotely sensed data are needed to distinguish peatlands from other wetlands and to estimate peat thickness (a critical indicator of peatlands' carbon stores); field surveys are also urgently required to validate maps and peat thickness estimates derived from this remotely sensed data (Crump 2017; Bourgeau-Chavez et al. 2018; FAO 2020). An international collaboration of scientists recently developed an innovative approach that combines these different methods and data sources to accurately map Indonesia's peatlands (Lyons 2018), but increased investments in these efforts are needed to bridge this critical knowledge gap globally.

Finally, it is important to note that, while they have a critical role to play in protection and restoration efforts, improvements in global-scale monitoring of ecosystems' extent are not a panacea. Inherent model uncertainty, as well as limitations associated with global-scale mapping based on medium-resolution satellite data, can lead to inaccuracies at the local level. Similarly, developing appropriate and equitable policy responses also requires an understanding of the complex local dynamics associated with human-driven ecosystem change, which cannot be captured in satellite imagery (Molinario et al. 2020).

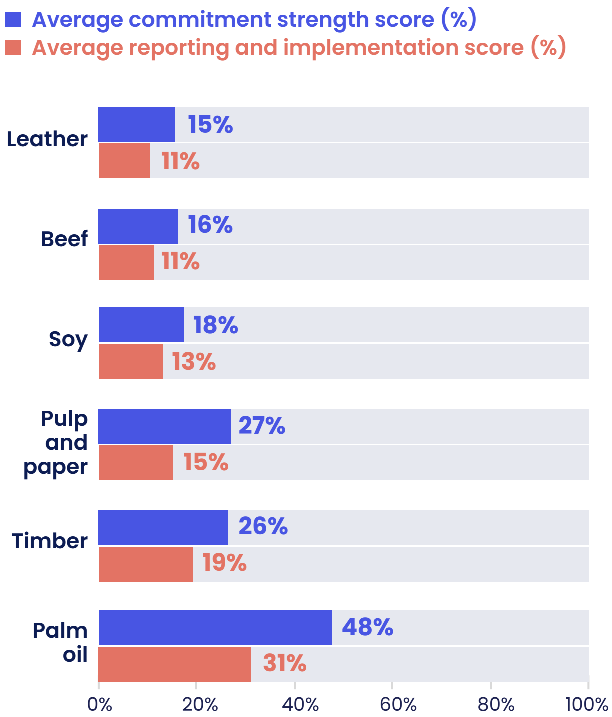
Improve supply chain interventions

The production of agricultural commodities, including beef, soy, palm oil, and wood fiber, drives much of deforestation globally (Curtis et al. 2018). Facing growing pressure to halt and reverse forest loss, 447 producers, processors, traders, manufacturers, and retailers have made at least 865 public commitments to reduce forest loss (IPCC 2022b). However, a third of the 350 companies most exposed to tropical deforestation risks have yet to adopt even a single commodity-specific deforestation commitment. Just 99 companies have established deforestation commitments for all forest-risk commodities in their supply chains, and only 7 have made the "strongest pledges" to completely eliminate conversion of all natural landscapes, including deforestation, and human rights abuses from their supply chains for at least one commodity. None has made such a commitment for all commodities (Forest 500 2022b).

Not only do corporate commitments fall short on ambition, but many companies also struggle to implement their pledges effectively, including developing robust implementation plans (Figure 57). To date, there is little evidence that voluntary corporate action has spurred long-term reductions in deforestation (Taylor and Streck 2018; IPCC 2022b). Third-party certification schemes are among the most popular avenues companies take to realize their pledges (Rothrock et al. 2022), yet they often reward those who can comply easily. Member companies of the Roundtable on Sustainable Palm Oil, for example, preferentially certified land deforested decades ago (Lambin et al. 2018). Similarly, sector-wide approaches like moratoria risk displacing forest loss to neighboring regions with fewer regulations, while internal production and sourcing policies often transfer compliance costs onto small-scale producers. Critical steps to address these challenges include expanding the scope of corporate actions to avoid leakage, improving efforts to transparently trace commodities across supply chains to increase compliance among all actors, and providing assistance to small-scale producers to incentivize implementation of deforestation standards. Complementary conservation policies, as well as strong enforcement, are also needed to support company action across producer countries (Lambin et al. 2018; Taylor and Streck 2018).

Similarly, countries responsible for importing deforestation embodied in commodities can help incentivize more ambitious corporate action, as well as increase demand for sustainably sourced commodities, by establishing labeling requirements, public procurement policies for sustainably sourced goods, and investor standards (Lambin et al. 2018). Some governments are going a step further to regulate imported commodities. The United Kingdom, the Netherlands, Norway, and France, for example, have placed some restrictions on goods associated with high levels of deforestation, and the European Union is currently considering adopting regulations that would require companies to comply with due diligence rules designed to prevent the entry and exit of goods produced on deforested land. Evidence assessing the impact of these relatively new policies on deforestation, however, remains limited (Walker et al. 2013), with one recent analysis finding that import restrictions alone may not significantly reduce deforestation and could provoke counterproductive backlash in producer countries (Busch et al. 2022). Rather, these demand-side regulations, if implemented, should be paired with policies that increase financial incentives to producer countries; unless these standards are implemented widely across consumer countries, commodities associated with high deforestation will likely shift to other regions without import restrictions (Busch et al. 2022).

FIGURE 57 | Commitment strength and reporting and implementation scores for Forest 500 companies



Note: According to Global Canopy, the "strongest pledges" include those that commit companies' supply chains to be free from deforestation and conversion of all natural ecosystems, as well as free from associated human rights abuses, with commitments specifically on free prior and informed consent, labor rights, and land-use conflict. This figure compares scores on the average strength of companies' commitments with scores on companies' implementation and reporting. See Forest 500 (2022a) for more information on the methodology used to score companies' commitments, reporting, and implementation.

Source: Forest 500 (2022b).

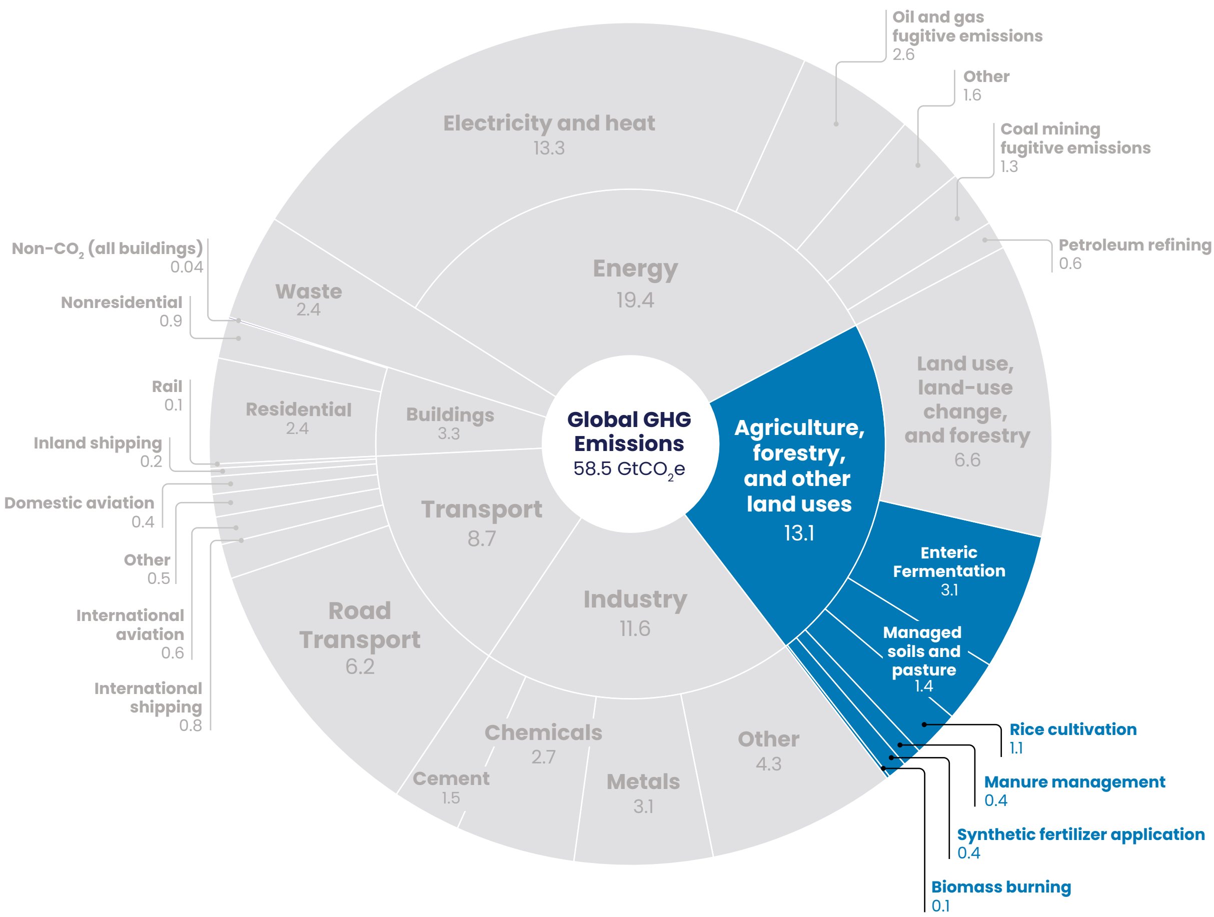
SECTION 7

Food and Agriculture

As the world's population climbs from roughly 8 billion in 2022 to nearly 10 billion by 2050 (UNDESA 2019), 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 work in agriculture (World Bank n.d.). Global food demand is on track to rise by 45 percent between 2017 and 2050 (Searchinger et al. 2021) based on estimates of population growth, rising meat consumption, and biofuels policies. Yet, as of 2021, between 700 and 800 million people were affected by hunger, an amount that rose sharply due to the effects of COVID-19 (FAO 2022b), and more than 3 billion people could not afford a healthy diet as of 2017 (FAO et al. 2021). Taken together, recent research shows that achieving global food security in the coming decades, while limiting warming to 1.5°C, cannot be done without significant changes to food production and consumption (Clark et al. 2020). Shifting demand, increasing productivity, and changing on-farm practices and technologies, combined, are necessary to reduce global emissions and the land footprint of the sector.

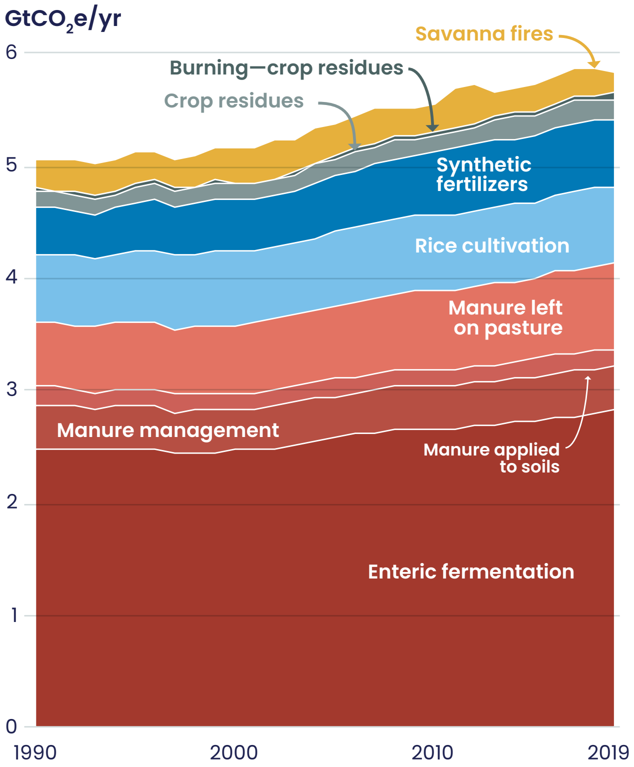
Direct GHG emissions from agricultural production, including from cropland and pastures, remain a significant, still-growing contributor to global GHG emissions (Figures 58 and 59),[62] increasing by an annual average of

FIGURE 58 | AFOLU's contribution to global GHG emissions in 2019



Notes: CO_2 = carbon dioxide; GHG = greenhouse gas; $GtCO_2e$ = gigatonnes of carbon dioxide equivalent.
Source: Minx et al. (2022), described in Minx et al. (2021) and used in IPCC (2022b).

FIGURE 59 | Global GHG emissions from agricultural production



Note: GHG = greenhouse gas; $GtCO_2e/yr$ = gigatonnes of carbon dioxide equivalent per year
Source: FAOSTAT (2022).

0.6 percent since 2000. In 2019 alone, crop and livestock production directly generated about 5.8 $GtCO_2e$ emissions, accounting for about half of AFOLU emissions. When these direct, production-related emissions are combined with ones from land-use change, energy-related emissions across food supply chains, and methane emitted from food waste in landfills, total agri–food system emissions accounted for about 16 $GtCO_2e$ per year, or around 30 percent of global GHG emissions in 2018 (Tubiello et al. 2022).

Critical shifts are needed in the agriculture sector to achieve global food security and limit warming to 1.5°C. These include shifting to low-carbon agricultural practices (Indicator 1), sustainably increasing crop yields and ruminant meat productivity (Indicators 2–3), dramatically lowering food loss and waste (Indicators 4–5), and shifting to more sustainable diets, namely by reducing ruminant meat intake in high-consuming regions (Indicator 6) (Table 9). These shifts will be necessary in order to ease competition for land and achieve the targets to protect and restore carbon-rich ecosystems discussed in Section 6 (Land Indicators 1–6).

TABLE 9 | Summary of global progress toward food and agriculture targets

INDICATOR	MOST RECENT DATA POINT (YEAR)	2030 TARGET	2050 TARGET	TRAJECTORY OF CHANGE	ACCELERATION FACTOR	STATUS
Agricultural production GHG emissions ($GtCO_2e/yr$)	5.8 (2019)	4.6	3.6		N/A; U-turn needed	
Crop yields (t/ha/yr)	6.6 (2020)	7.8	9.6		6x	
Ruminant meat productivity (kg/ha/yr)	27 (2019)	33	42		1.3x	!
Share of food production lost (%)	14 (2016)	7	7		Insufficient data	?
Food waste (kg/capita/yr)	121 (2019)	61	61		Insufficient data	?
Ruminant meat consumption (kcal/capita/day)	91 (2019)	79	60		5x	

Notes: $GtCO_2e/yr$ = gigatonnes of carbon dioxide equivalent per year; kcal/capita/day = kilocalories per capita per day; kg/capita/yr = kilograms per capita per year; kg/ha/yr = kilograms per hectare per year; t/ha/yr = tonnes per hectare per year.
Sources: Historical data from FAOSTAT (2022), FAO (2019), and UNEP (2021d); targets from Searchinger et al. (2019b) and United Nations (2015).

Status of food and agriculture indicators

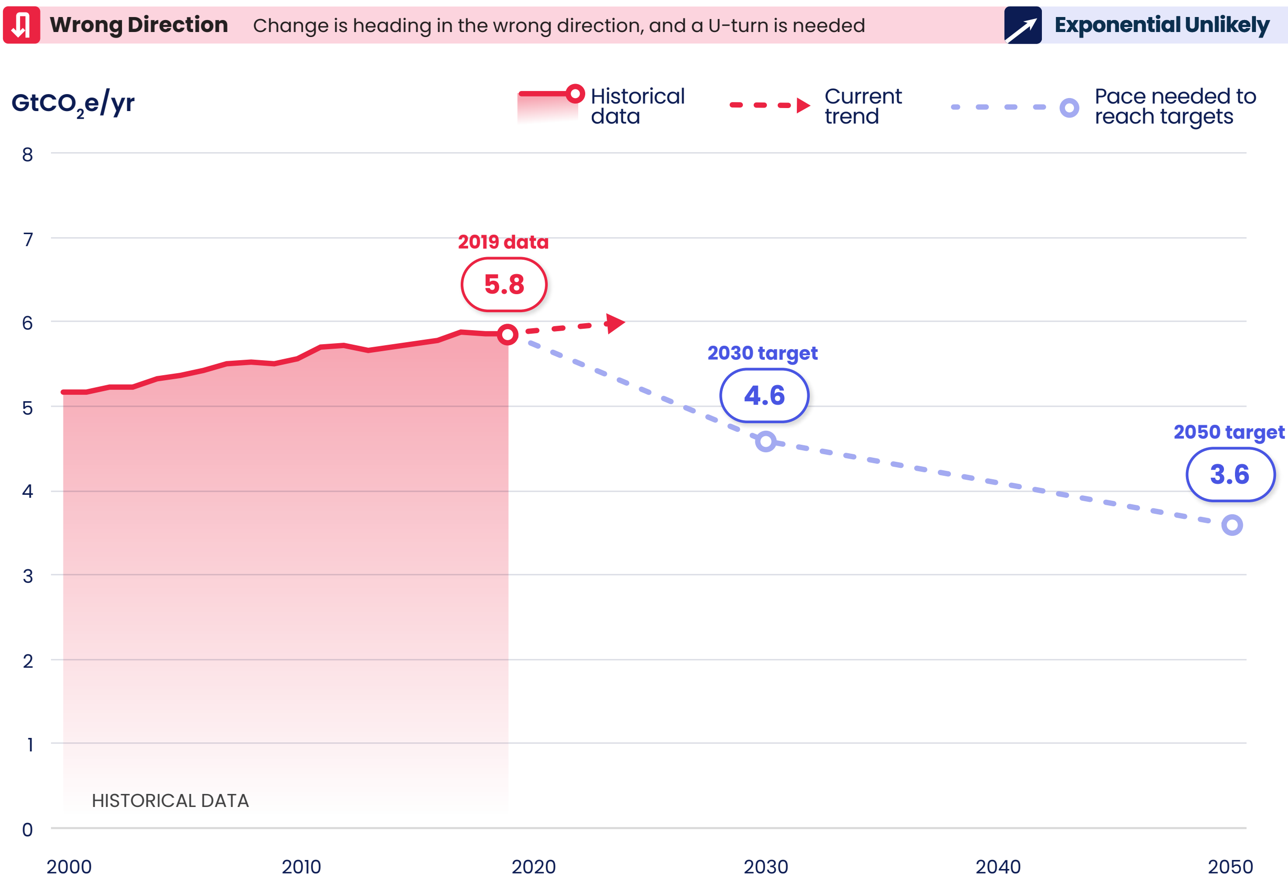
FOOD AND AGRICULTURE INDICATOR 1: Agricultural production GHG emissions ($GtCO_2e/yr$)

- **Targets**: Global GHG emissions from agricultural production decline 22 percent by 2030 and 39 percent by 2050, relative to 2017.

Global agricultural production emissions increased about 2 percent between 2015 and 2019 (Figure 60; Box 6). A closer look at the disaggregated agricultural emissions sources (Table 10) shows that enteric fermentation, manure on pasture, and soil fertilization emissions grew during this period, and together these three sources accounted for 74 percent of total agricultural production emissions in 2019 (FAOSTAT 2022; FAO 2022a). Manure management emissions and methane from rice cultivation were stable during this period.[63]

While it is encouraging that agricultural production emissions are not growing quickly, targets for 2030 and 2050 call for significant reductions, so a major step change is still needed (Figure 60).

FIGURE 60 | Historical progress toward 2030 and 2050 targets for agricultural production GHG emissions

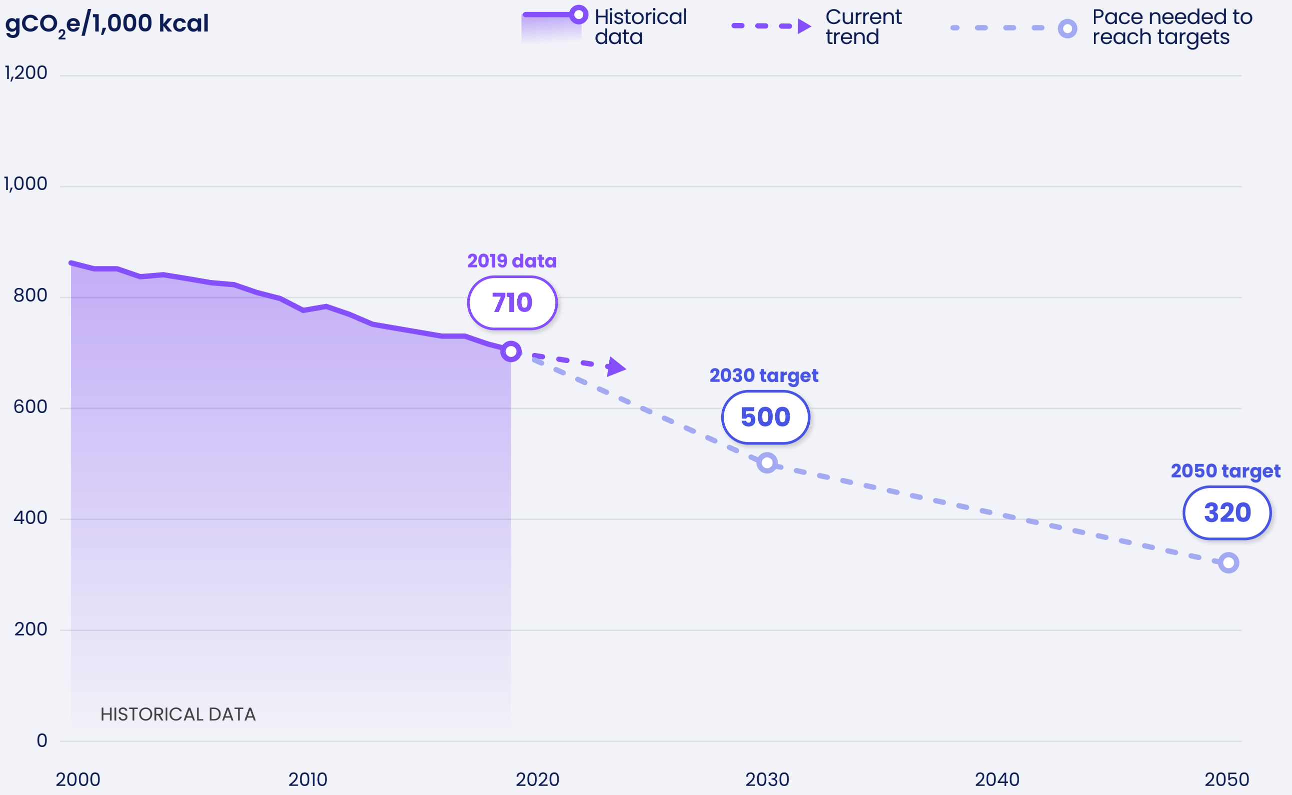


Note: $GtCO_2e/yr$ = gigatonnes of carbon dioxide equivalent per year.
Sources: Historical data from FAOSTAT (2022); 2030 and 2050 targets derived from Searchinger et al. (2019b).

BOX 6. EMISSIONS INTENSITY OF AGRICULTURAL PRODUCTION

While total agricultural emissions have not peaked, the emissions intensity of agricultural production, as measured in grams of CO_2e per 1,000 kilocalories (kcal)[a] in the global food supply, fell by 4 percent between 2015 and 2019, continuing a decades-long trend (Figure B6.1). The declining emissions intensity of agricultural production is largely driven by improved efficiencies in crop and livestock production. But to feed nearly 10 billion people by 2050 while keeping warming to 1.5°C, emissions intensity would need to decrease roughly three times faster than its annual rate of change from 2015 to 2019. Changes to food production practices, as well as food consumption patterns (e.g., amount of food loss and waste, share of animal-based foods in diets, share of agricultural products used as bioenergy), can help achieve this required decline.

FIGURE B6.1 | Trends in GHG emissions from agricultural production per 1,000 kcal



Notes: gCO_2e/1,000 kcal = grams of carbon dioxide equivalent per 1,000 kilocalories

Sources: Historical data from FAOSTAT (2022); 2030 and 2050 targets derived from Searchinger et al. (2019b).

[a] *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. That said, data on production and consumption of calories are available in FAOSTAT (2022) 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.*

TABLE 10 | Disaggregated GHG emissions reductions targets by major sources of agricultural production GHG emissions

EMISSIONS SOURCE	RECENT TREND (2015–19)	2030 TARGET, RELATIVE TO 2017	2050 TARGET, RELATIVE TO 2017
Enteric fermentation	+3%	-17%	-29%
Manure management	0%	-21%	-39%
Manure on pasture	+6%	-14%	-20%
Soil fertilization	+2%	-24%	-40%
Rice cultivation	0%	-23%	-46%
Total	**+2%**	**-22%**	**-39%**

Note: GHG = greenhouse gas.
Sources: Historical data from FAOSTAT (2022); 2030 and 2050 targets derived from Searchinger et al. (2019b).

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

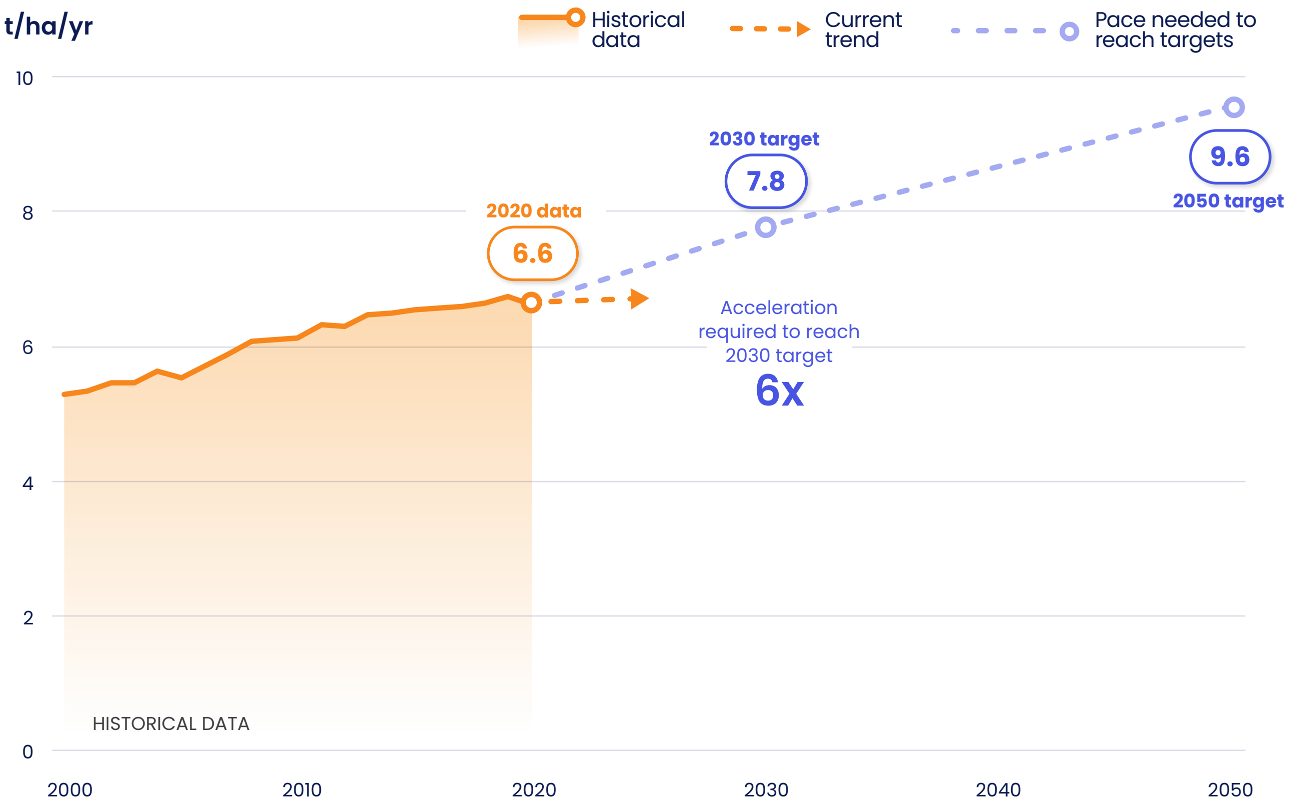
- **Targets**: Crop yields increase by 18 percent by 2030 and 45 percent by 2050, relative to 2017.

Global crop yields, expressed in terms of tonnes of crops produced per hectare of cropland,[64] dipped in 2020 relative to 2019, falling to only 0.5 percent above 2016 levels (Figure 61). Because of this, recent growth in yields needs to accelerate by six times to reach the 2030 target, meaning that this progress made globally is well off track (unlike in Boehm et al. 2021, in which data for this indicator came from before the 2019–20 decline, and progress was classified as merely "off track"). Yields in Africa also continued to stagnate at a low level; for example, in 2020, yields of cereal crops in Africa, which are critical for food security, were only 40 percent of the world average (Figure 62). Improving crop yields on small farms in Africa is also a key lever for reducing poverty (IFPRI 2022).

Improving yields on existing agricultural land has the potential to reduce agricultural expansion and spare forests and other ecosystems. Observations from multiple continents—along with modeling studies—found that linking yield improvements with ecosystem protection has the highest potential to maximize land-based carbon stocks, while meeting demand for land-based products (Williams et al. 2018). These improvements, however, must be accompanied by strong forest governance (Garrett et al. 2019). New 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 million hectares (Mha) of land were converted to 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 is dominant in South America, in Africa, short-term cultivation of subsistence crops (or shifting agriculture) seems to be the biggest contributor to expansion (Curtis et al. 2018).

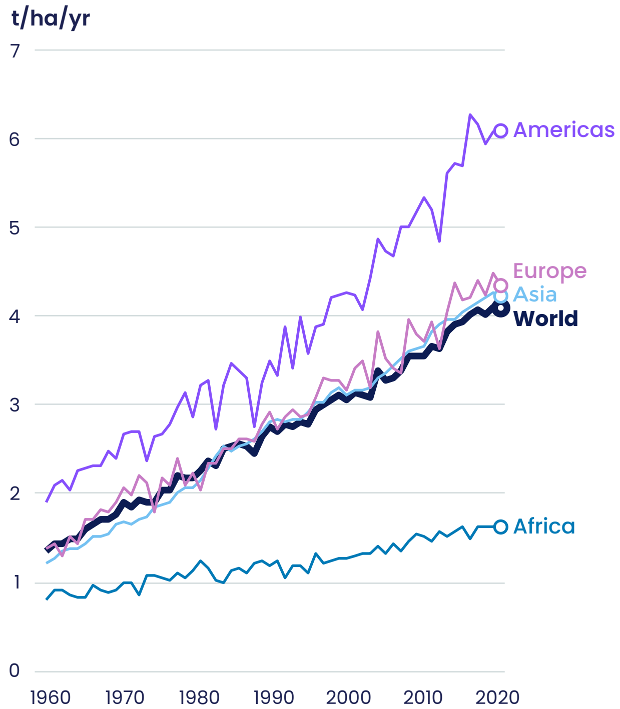
FIGURE 61 | Historical progress toward 2030 and 2050 targets for crop yields

Well Off Track Change is heading in the right direction, but well below the required pace **Exponential Unlikely**



Note: t/ha/yr = tonnes per hectare per year.
Sources: Historical data from FAOSTAT (2022); 2030 and 2050 targets derived from Searchinger et al. (2019b).

FIGURE 62 | Trends in regional cereal yields



Note: t/ha/yr = tonnes per hectare per year.
Source: FAOSTAT (2022).

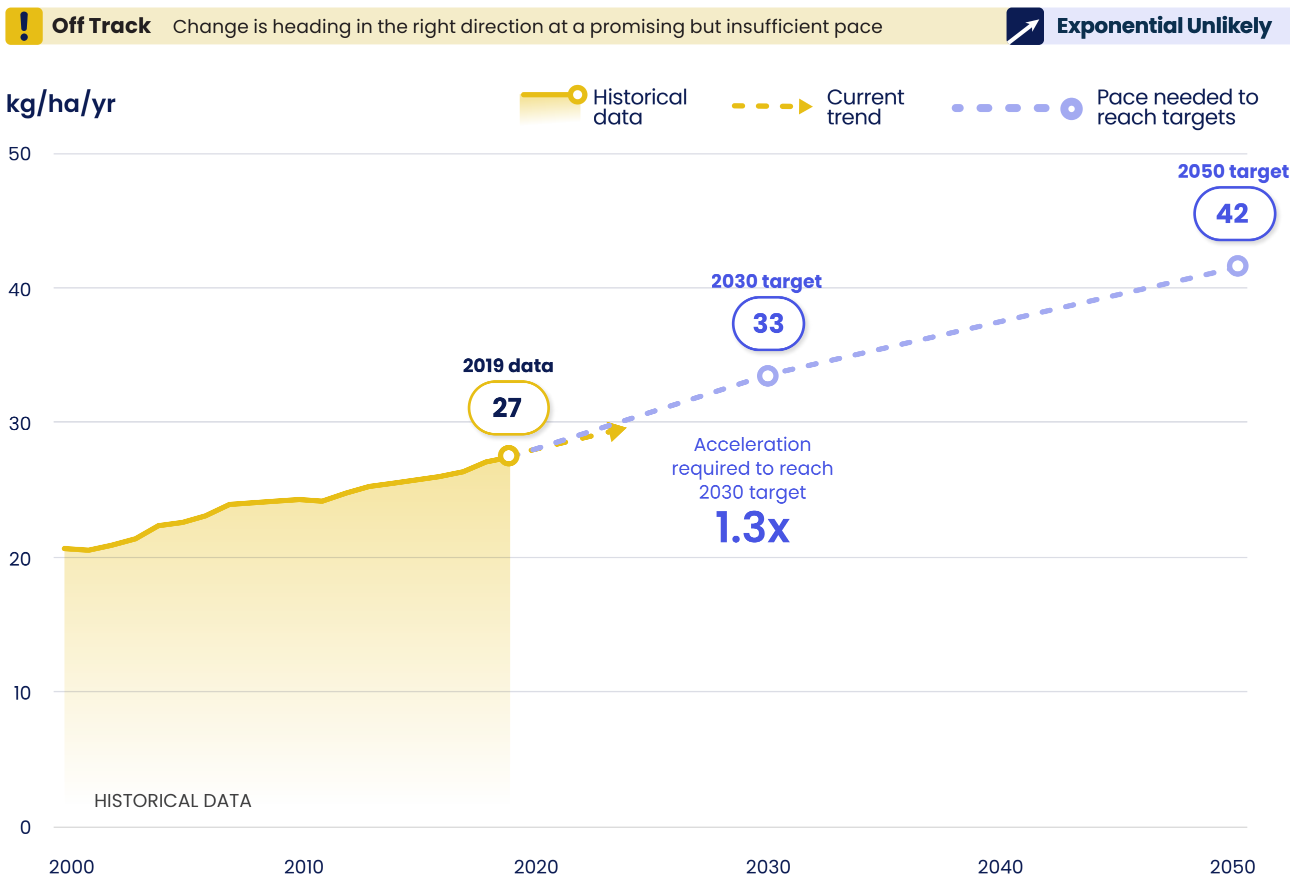
FOOD AND AGRICULTURE INDICATOR 3:

Ruminant meat productivity (kg/ha/yr)

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

Ruminant meat productivity is the amount of meat from cattle, sheep, goats, and other ruminants produced per hectare of pastureland. Ruminant meat productivity per hectare increased to a new high in 2019, growing by 7 percent between 2015 and 2019 (Figure 63). The basic mechanisms for these productivity gains have been improvements in feed efficiency, improvements in pasture and grazing systems, and increases in meat production per animal (e.g., through improved breeds or better veterinary care) (Searchinger et al. 2019b). Yet, to meet the 2030 target, recent growth must still accelerate by 1.3 times, meaning that, while progress is heading in the right direction, it remains off track. Satellite-based evidence of deforestation (Goldman et al. 2020) shows that 45 Mha of forest was replaced by pastureland for cattle grazing between 2001 and 2015, mainly in South America, suggesting that pasture expansion is still occurring to keep pace with global ruminant meat demand growth in the 21st century.

FIGURE 63 | Historical progress toward 2030 and 2050 targets for ruminant meat productivity



Note: kg/ha/yr = kilograms per hectare per year.

Sources: Historical data from FAOSTAT (2022); 2030 and 2050 targets derived from Searchinger et al. (2019b).

FOOD AND AGRICULTURE INDICATORS 4 AND 5:

Share of food production lost (%) and food waste (kg/capita/yr)

- **Targets**: The share of food production lost declines 50 percent by 2030, relative to 2016, and these reductions are maintained through 2050.
- **Targets**: Worldwide per capita food waste is reduced by 50 percent by 2030, relative to 2019, and these reductions are maintained through 2050.

Food loss occurs before food gets to market, during harvest, storage, and transport to market; whereas food waste occurs at retail markets, restaurants, or in homes. Because global data are not yet available through the Food Loss Index (FAO 2019) and Food Waste Index (UNEP 2021d), we cannot yet assess recent global progress between the baseline years and the 2030 targets to reduce food loss and waste rates by 50 percent (United Nations 2015). The most recent global estimates (from 2016) remain that 14 percent of global food production is lost between the farm gate and processing stages of the food supply chain (FAO 2019) (Figure 64), and that 17 percent of food at the retail level (or 121 kg per person per year) is wasted in households, food service, and retail (UNEP 2021d) (Figure 65).

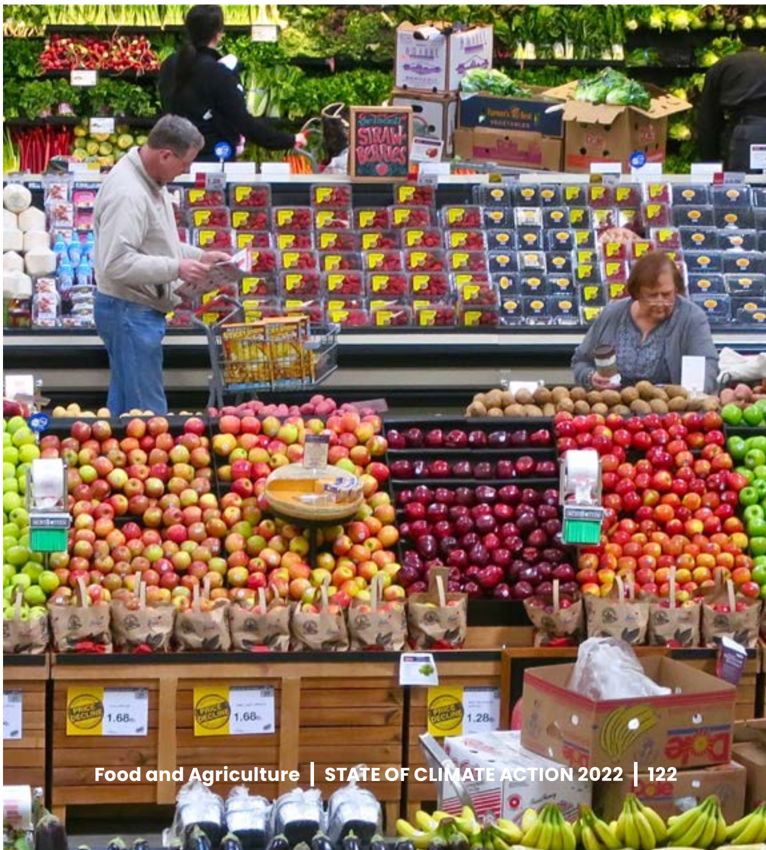
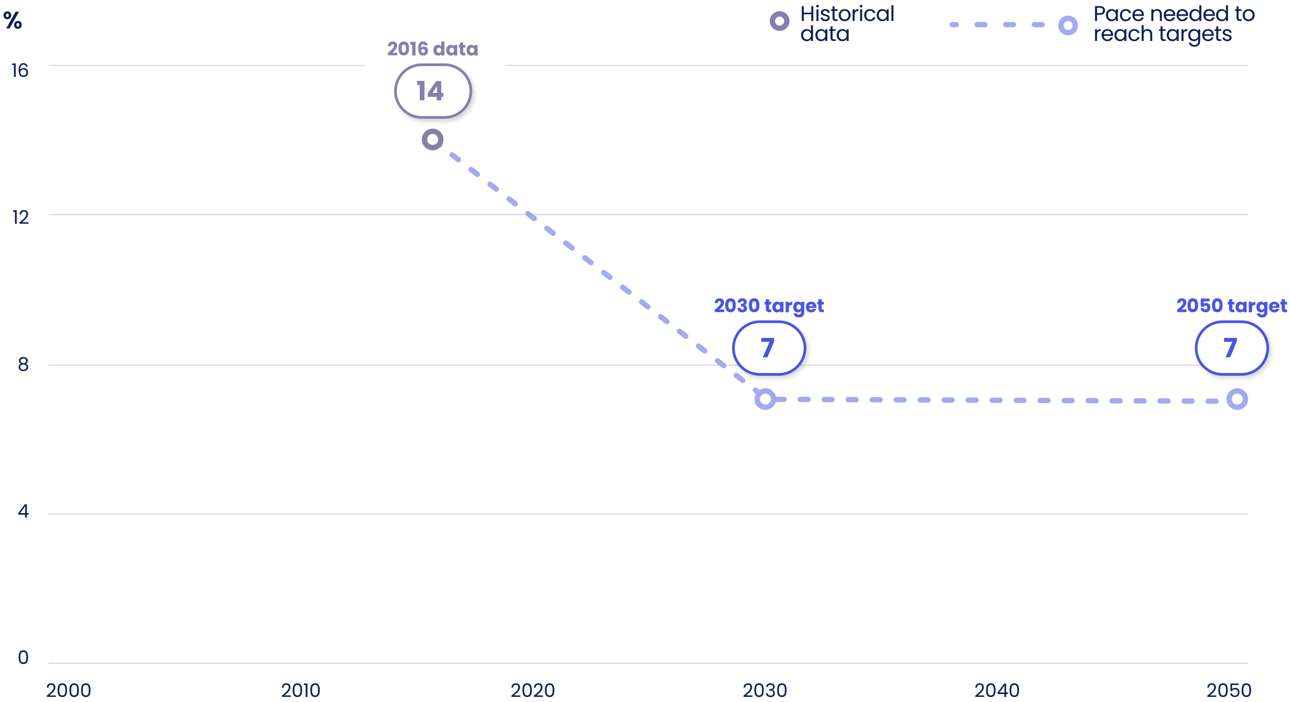


FIGURE 64 | Historical progress toward 2030 and 2050 targets for share of food production lost

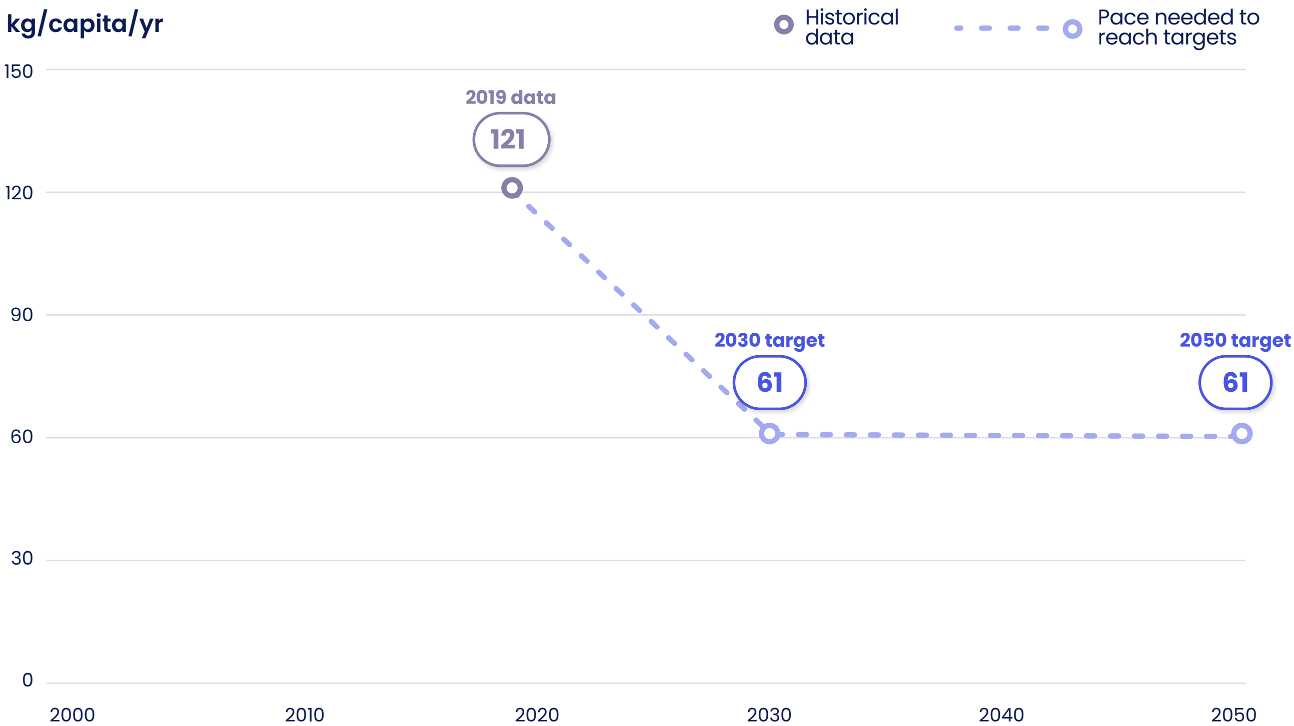
Insufficient Data Data are insufficient to assess the gap in action required for 2030 **Exponential Unlikely**



Note: Food loss occurs before food gets to market.
Sources: Historical data from FAO (2019); 2030 and 2050 targets derived from United Nations (2015).

FIGURE 65 | Historical progress toward 2030 and 2050 targets for food waste

Insufficient Data Data are insufficient to assess the gap in action required for 2030 **Exponential Unlikely**



Note: kg/capita/yr = kilograms per capita per year. Food waste occurs at the retail level and in homes, restaurants, etc.
Source: Historical data from UNEP (2021d); 2030 and 2050 targets derived from United Nations (2015).

FOOD AND AGRICULTURE INDICATOR 6:

Ruminant meat consumption (kcal/capita/day)

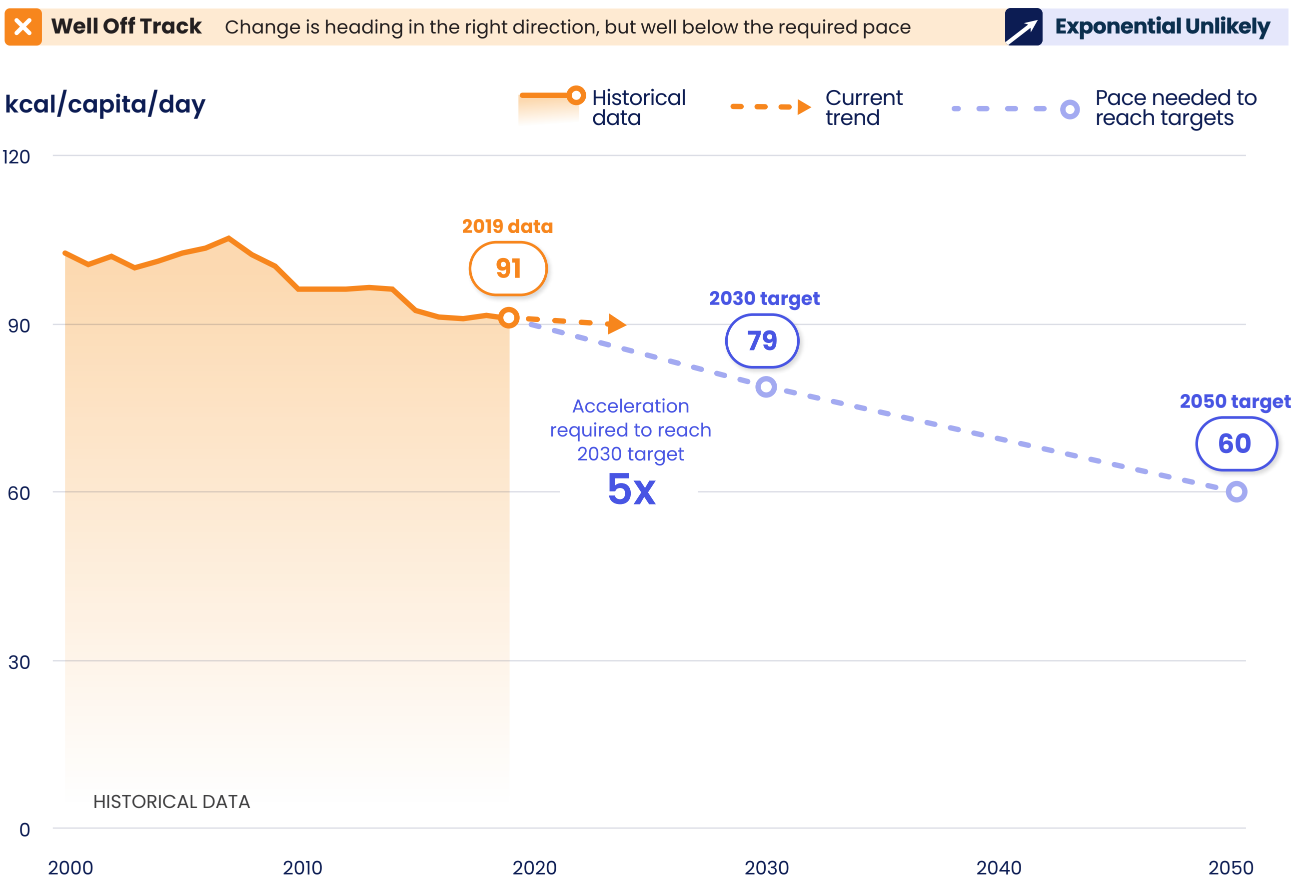
- **Targets**: Across high-consuming regions (the Americas, Europe, and Oceania),[65] daily per capita ruminant meat consumption[66] decreases to 79 kilocalories by 2030 and to 60 kilocalories by 2050.

Per capita consumption of beef, lamb, and goat meat across high-consuming regions fell by 1.5 percent between 2015 and 2019, reaching 91 kilocalories per capita per day in 2019 (FAOSTAT 2022). However, this rate of decline would need to be five times faster to hit the 2030 target of 79 kilocalories per person per day (Figure 66).

Each of the three high-consuming regions—the Americas, Europe, and Oceania—saw a decline in per capita consumption between 2015 and 2019. Across the Americas and Europe, per capita consumption fell by 0.9 percent and 2.9 percent respectively, while in Oceania, it dropped by 11.2 percent.

While other regions were still far below the 60-kilocalorie threshold in 2019 (e.g., Africa at 40 and Asia at 36)—and thus a goal of reducing ruminant meat consumption is not relevant—certain countries (e.g., China) are experiencing significant increases and will likely reach the 60-kilocalorie threshold between now and 2050. In such cases, it would be advisable to try to peak per capita ruminant meat consumption early so as not to breach the target, and instead aim to shift demand to lower-GHG protein sources.

FIGURE 66 | Historical progress toward 2030 and 2050 targets for per capita ruminant meat consumption in the Americas, Europe, and Oceania



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.

Sources: Historical data from FAOSTAT (2022); 2030 and 2050 targets derived from Searchinger et al. (2019b).

Global assessment of progress for food and agriculture

Four interconnected strategies are needed to sustainably feed a growing world population while ending ecosystem degradation and loss and holding global warming to 1.5°C:

- **Produce** more food and feed on existing agricultural lands, while reducing agricultural production emissions. Overall, the emissions intensity of agricultural production has been declining while total agricultural production emissions are still growing (Indicator 1). Similarly, crop yields (Indicator 2) and ruminant meat productivity (Indicator 3) are growing, but so is agriculture's total land footprint—putting pressure on forests and other remaining natural ecosystems.
- **Protect** remaining natural and seminatural ecosystems (e.g., forests, wetlands, grasslands) from conversion and degradation. Ecosystem protection is covered in Section 6 (Land Indicators 1, 3, and 5).
- **Reduce** projected growth in demand for land-intensive goods, particularly by high-income consumers. More data are needed to have a global picture of progress in reducing food loss and waste (Indicators 4 and 5). Per capita ruminant meat consumption is falling in high-consuming regions (Indicator 6) but not yet at the pace necessary to achieve the 2030 and 2050 targets laid out in the previous section.
- **Restore** degraded ecosystems and marginal agricultural land (with limited improvement potential) back to nature. Ecosystem restoration is covered in Section 6 (Land Indicators 2, 4, and 6).

In short, efficiency improvements in agriculture and the wider food system, while encouraging, are not yet keeping pace with continued global food demand growth. And if agriculture's land footprint continues to expand and emissions from food production continue to grow, global goals to eliminate deforestation and peatland degradation, achieve hundreds of millions of hectares of restoration (Land Indicators 1–6), and keep global warming within 1.5°C will be out of reach.

Crucially, accelerating productivity gains—in a changing climate—will need to be done in ways that safeguard soil and freshwater resources and minimize water and air pollution. However, gains in productivity could lead to extensification into natural ecosystems. This is why incentives for productivity improvements will need to be linked to natural ecosystem protection, equity, and restoration, to combat the potential rebound effect (Searchinger et al. 2019b).

In addition to productivity gains and efficiency improvements, meeting climate goals will require reducing food loss and waste (Indicators 4 and 5) and shifting to healthier and more sustainable diets (which, from a climate perspective, particularly includes reducing ruminant meat consumption in high-consuming countries, Indicator 3).

Food production is extremely vulnerable to climate change. The IPCC's Sixth Assessment Report finds that climate change is already stressing agriculture, fisheries, and aquaculture. Heat extremes, drought, and other climate-related hazards have reduced agricultural productivity, disrupting food supplies and livelihoods. Since 1961, crop yield growth in Africa has shrunk by a third due to climate change. Compounding these existing challenges, risks and vulnerabilities in the sector are very likely to worsen in a warmer climate. For example, under a high-emissions scenario, 10 percent of agricultural area currently cultivated could be climatically unsuitable by 2050 (IPCC 2022b).

Major transformations 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, it will be essential that they are able to meaningfully participate in design, implementation, and governance of adaptation and mitigation strategies, especially smallholders, women, and other vulnerable groups. This 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).

In 2021 food and agriculture climbed up the climate agenda. The inaugural UN Food Systems Summit, held in September 2021, helped call attention to the need for a more sustainable, healthy, and equitable food system. It included specific action tracks around safe and nutritious food, sustainable production and consumption, equitable livelihoods, and building resilience. At COP26, world leaders signed the Glasgow Leaders' Declaration on Forests and Land Use, which included several references to the need to advance more sustainable agricultural production as part of a global goal to halt and reverse forest loss and land degradation by 2030. In addition, leaders signed the Global Methane Pledge to reduce methane emissions by 30 percent by 2030. The attention to reducing methane emissions will necessarily include mitigation in the agriculture sector, which accounts for at least 40 percent of human-caused methane emissions (UNEP 2021g).

Achieving the targets in this section will require overcoming a number of challenges. First, the effects of the COVID-19 pandemic, which caused economic downturns and spikes in food insecurity around the world, are still being felt. COVID-19 has affected all parts of food supply chains, from direct effects on workers' and consumers' health, to lockdowns, travel and trade disruptions, employment, food shortages, and increases in food prices. Households headed by women, or with lower levels of education, income, or savings, have suffered higher rates of food insecurity since the start of the pandemic (Dasgupta and Robinson 2022). Although measures taken to protect food supply chains as "essential services"—along with social safety net policies such as cash and food assistance—have helped maintain food supplies and access, many challenges remain.

A second ongoing challenge is conflict. Russia's invasion of Ukraine in February 2022—in addition to the immediate humanitarian consequences, including shortages of food and water as people fled the fighting—has driven up food, fuel, and fertilizer prices that had already been rising for months due to COVID-19 supply chain disruptions, the impact of climate change on yields, and financial speculation. Russia and Ukraine are major exporters of wheat, maize, barley, and sunflower oil, and Russia is a leading fertilizer producer. Price spikes, in turn, threaten global food security—especially affecting poorer people's ability to purchase food. National decision-makers are weighing whether to plow up natural or fallow areas to increase domestic food production, change agricultural trade policies, or substitute domestic bioenergy in the face of high energy prices and constrained energy supplies. Each of these decisions has potentially significant consequences for longer-term food security and the effects of the food system on the climate.

Enabling conditions for climate action across food and agriculture

The projected growth in global demand for crop and livestock products in the coming years and decades presents a major challenge in a world that needs to peak and reduce emissions from food production and associated land-use change, all the while adapting to a changing climate. The connections between climate change and agriculture have only recently gained international attention, and the transition toward a sustainable, low-carbon sector is in its early stages. No one technology or practice can transform the agriculture sector, which produces a diversity of products in heterogeneous socioeconomic environments. Innovations in practices, technologies, policies, and financing will be needed across supply and demand.

Because practices and technologies that reduce agricultural production emissions may entail additional costs to producers, further incentives and regulatory frameworks will be necessary to help farmers shift to more climate-friendly practices and technologies once they are available. Another major barrier is financial support for the transition to sustainable agriculture. The sector receives little climate finance given the scale of the climate impact it could deliver. Public finance in the

past has been moving the sector in the wrong direction and needs to be shifted toward making agriculture more sustainable.

Below we discuss five enabling conditions that could help overcome these barriers, including the redirection of existing agricultural support and approaches that pair efforts to increase yields with those to protect carbon-rich ecosystems ("produce and protect"); inclusive consultation processes and secure land rights; demand shifts; technical assistance and finance; and investments in research, development, and demonstration (RD&D).

Redirect existing agricultural support and pair efforts to increase yields with those to protect carbon-rich ecosystems

Public finance, which represents the majority of investment in the sector (IFPRI 2022), urgently needs to shift toward innovations that promote mitigation and adaptation. Domestic financing can be counterproductive to reducing emissions by supporting unsustainable practices and emissions-intensive products, such as beef and rice (UNEP 2021h), and by undervaluing natural resources. In wealthy countries, agricultural support typically benefits high-income commercial farmers, while denying poorer farmers access to markets (IFPRI 2022).

Agricultural policies provided about $620 billion a year in farm support worldwide in 2019 (IFPRI 2022). These agricultural subsidies can be in the form of market supports (e.g., tariffs or import limits), direct payments, or tax credits. An analysis of agricultural support for 2014 through 2016 found that only 5 percent of these subsidies supports conservation or climate objectives, and only 6 percent supports research and technical assistance (Searchinger et al. 2020).

Fertilizer subsidies, specifically, have encouraged high levels of fertilizer use in several countries, which leads to more nitrous oxide emissions and increased air and water pollution. Redirecting even a portion of subsidies around the world to climate objectives and research and development could help accelerate innovation and uptake of low-emissions technologies and practices. This domestic support could also be used to monitor and reduce food loss and waste within a country (Indicators 4 and 5).

Beyond phasing out or redirecting fertilizer subsidies, governments can condition public support for agricultural producers on environmental safeguards or outcomes, such as the protection of forests, peatlands, or mangroves. For example, a farmer or rancher may only receive payments if their land has not been recently cleared. In 2008, the Brazilian National Monetary Council introduced a resolution that conditioned rural credit in the Amazon on proof of a farmer's or rancher's compliance with legal and environmental regulations. This policy, in combination with strong forest governance, enabled declines in deforestation between 2009 and 2011 (Assunção et al. 2013; Searchinger et al. 2019b). Similarly, in the United States, a farmer cultivating highly erodible land must have a conservation plan in place to be eligible for crop insurance payouts (USDA n.d.).

Establish inclusive consultation processes and secure land rights

To meet climate and development goals, the agriculture sector needs to contribute to inclusive economic and social development to help reduce poverty. About 2 billion people are employed in the sector, and more than 70 percent of the world's poor live in rural areas, where most depend on agriculture for their livelihood. Growth in the agricultural sector reduces poverty more effectively than growth originating in other economic sectors (Christiaensen et al. 2011). Equitable economic growth will depend on inclusive consultation processes, which should include farmers, ranchers, and other communities affected by the transition toward sustainable livelihoods. These processes can help ensure that the benefits of the zero-carbon and resilient economy are shared fairly. One example of such a process is the involvement by CGIAR (the former Consultative Group for International Agricultural Research) of women farmers in crop breeding in Peru. CGIAR is involving women early in the research and development process to develop a more nutrient-dense potato variety that is attractive to local farmers (Polar 2021). Although the results of this initiative have yet to be evaluated, previous research by CGIAR's Gender Platform found that women's empowerment in agriculture improved food security and food affordability (Lane 2022).

As part of redirecting support measures mentioned above, countries can also identify regressive subsidies in the sector and redirect them to help vulnerable communities shift to climate-resilient practices. Long-term climate strategies should plan for the social protections required to complement mitigation efforts.

As described in Section 6, Indigenous Peoples and local communities are among the most effective communities at protecting and sustainably managing the land and forests that they live in and depend on. Lack of land tenure rights impacts farmers' ability to implement practices to improve environmental outcomes. Without a guarantee that farmers will reap the benefits of their investments in time, labor, and money, they will likely have little incentive to adopt improved management practices. For example, lack of land tenure in Ghana created bureaucratic and legal hurdles to register trees on cocoa farms, impeding the farmers' ability to realize the benefits of agroforestry (IPCC 2022b). Land, resource, and property rights should be secured for Indigenous Peoples, women, and local communities as a path to poverty reduction, sustainable development, and environmental management. Ensuring that women have equal rights to seeds, land ownership, and market access is a key lever to increasing crop yields on small farms (IFPRI 2022).

Reduce waste and shift demand

Reducing growth in demand for food and other agricultural products—by reducing food loss and waste (Indicators 4 and 5) and shifting to healthier and more sustainable diets (Indicator 3)—will be critical in easing the challenges related to the sustainability of food production (Searchinger et al. 2021).

Food waste is doubly harmful to the climate as it wastes all of the inputs from producing food and it generates methane when it is disposed of.

Governments and companies have been using a Target-Measure-Act approach to reduce food loss and waste since the adoption of the Sustainable Development Goals (SDGs) in 2015. Countries and regions representing about half of the world's population have set targets in line with the SDG Target 12.3 (Lipinski 2020).

Measuring food loss and waste by companies and governments can help identify opportunities to save money and prevent food loss and waste. The United

Kingdom, Japan, and the United States were among the first countries to measure food loss and waste at the national level during the 2010s. Other countries have more recently established measurement efforts, and UN agencies are coordinating the Food Loss Index (FAO 2019) and Food Waste Index (UNEP 2021d) to monitor progress at the global level and help standardize national government measurement efforts.

Between 2007 and 2018, the United Kingdom reduced food loss and waste per capita by 27 percent, making it the first country to be more than halfway to the 2030 SDG Target 12.3. To achieve this, the country set a target in line with SDG Target 12.3, completed four national food loss and waste measurements, led a collaboration with food companies to voluntarily reduce food loss and waste while providing companies with clear advice for food loss and waste reduction, innovated in food packaging and labeling, and directly engaged consumers with a "Love Food Hate Waste" campaign. The Netherlands also achieved a 29 percent reduction in household food waste between 2010 and 2019, with some similar success factors, including food loss and waste measurement, public-private partnerships, and consumer engagement (Lipinski 2020).

Many companies in the private sector have adopted targets aligned with SDG 12.3. The 10 × 20 × 30 initiative brings together 12 (increased from an initial 10) of the world's biggest food retailers and providers, each of which engages with 20 of their priority suppliers to aim to halve rates of food loss and waste by 2030. These nearly 200 companies publicly committed to a 50 percent reduction in food loss and waste within their supply chain, began measuring their food loss and waste, and started taking action to achieve that goal.

Businesses and governments have a significant potential to shift food consumption by using their purchasing power to procure food that is healthy and lower in emissions (Swensson and Tartanac 2020). Governments can identify policies and regulations (within agencies that deal with health, agriculture, water, and the environment) that influence diet choices and recommend changes to ensure that they are aligned with promoting these diets. These policies include the domestic support mentioned above and national dietary guidelines that influence food purchasing across governments, businesses, and households. Beyond policies, incentives, and "nudges" to shift consumption toward lower-emissions protein sources such as pulses and legumes, another lever for reducing ruminant meat consumption is reducing the price of newer alternative proteins such as plant-based and cultivated meat (as discussed in "Innovations in technologies, practices, and approaches: Investments in RD&D," below).

For businesses, through the Cool Food initiative and the Better Buying Lab, WRI works with restaurants, food service companies, universities, hospitals, and others to help them provide more climate-friendly options to consumers. Using cutting-edge behavioral science, WRI helps these businesses make changes in their operations that encourage diners to choose more sustainable, plant-rich options. For example, WRI research has shown that changing menu language to describe vegetarian dishes in more indulgent terms (think "hearty," "slow-roasted," or "creamy") in some cases doubled the likelihood that UK diners would order vegetarian meals (Wise and Vennard 2019).

Strengthen climate finance for mitigation and adaptation

The transition to sustainable agriculture is poorly funded given the scale of the climate impact it could deliver. An analysis by the Climate Policy Initiative (CPI) of all climate-related financial flows found that agriculture, forestry, and land uses received only about 2 percent of the total (for 2019–20), although the sector is responsible for over 20 percent of global greenhouse gas emissions (including more than 40 percent of anthropogenic methane emissions) (Buchner et al. 2021). International development funds, public (government) budgets, and national development banks represent the vast majority of this finance (IFPRI 2022). There is a strong case for increasing the volume of climate finance to this sector, given the risks posed by climate change to food security, as well as agriculture's contribution to global emissions.

Smallholder farmers (cultivating less than two hectares) in developing countries, in particular, need finance to purchase equipment or basic inputs to improve productivity. These smallholders cultivate roughly 24 percent of agricultural land and produce about 30 percent of the world's food (Ricciardi et al. 2018).

Private sources of funding into sustainable agriculture, from banking systems, capital markets, and corporations has been miniscule in the past, because investment in the sector is viewed to be too risky. At the same time, banks and investors continue to finance activities linked with fossil fuels and deforestation (IFPRI 2022). Proposed policies that would require companies to disclose emissions from their investments provide an incentive for the private sector to invest in agricultural operations aiming to sequester carbon and improve productivity.

Public and philanthropic finance can be leveraged to reduce the risk of investing in the sector and attract private capital. Combining different sources of finance for a project or operation is called blended financing, which enables public financing to leverage higher levels of private sector investment in the sector by reducing the risk for private finance. An example of a blended finance project is Sustainable Landscape Portfolio Guarantees in India, supported through a partnership between Rabobank Foundation and USAID, which aims to enable lending by local partner financial institutions to small-to-medium enterprises (SMEs), cooperatives, producer companies, and microfinance institutions engaged in sustainable landscape investments. Another example is the Private Agriculture Sector Support project in Tanzania, which provides credit guarantees issued by development agencies to commercial banks and local development finance institutions (DFIs) to incentivize their engagement in agri-SME lending by de-risking their loan activity to agribusinesses. Private Agriculture Sector Support guarantees provide high coverage ratios for specific loans, as they cover 60 percent or more of the loan amounts (Stacey 2021).

Broadly speaking, the transition to a lower-carbon, more climate-resilient agricultural sector will require funding for on-the-ground technical assistance from local agricultural extension services and farmer-led organizations to help farmers and ranchers determine their needs and the best innovations for adapting to climate change and mitigating emissions. In order to prevent improved productivity leading to land-use change, these financial instruments should be accompanied by technical assistance that supports the adoption of practices that increase productivity and climate resilience while protecting natural ecosystems.

Invest in RD&D

Innovations and technologies that boost productivity, reduce GHG emissions, shift consumption, or improve climate resilience are necessary to help the sector achieve its climate targets. Many important innovations—including alternative proteins to slow the growth in meat demand, feed additives to reduce methane emissions from ruminant livestock, nitrification inhibitors for fertilizers, and lower-methane rice varieties—are in various stages of RD&D.

Agricultural research has traditionally been focused on enhancing productivity. Looking ahead, this focus must broaden to include the larger set of social and environmental goals that are becoming increasingly important to ensure the sector's sustainability. RD&D of technologies and innovations that improve yields and reduce the emissions of powerful greenhouse gases, especially methane and nitrous oxide, will be key to meeting climate targets.

At COP26, an exciting new initiative focused on agricultural RD&D was launched by the governments of the United States and the United Arab Emirates. The Agriculture Innovation Mission for Climate (AIM for Climate) is a coalition of over 200 partners, including 41 countries, focused on accelerating agricultural innovation in line with climate change goals. Its members announced $4 billion of investment in climate-smart agriculture and food systems innovation at COP26, and, in February 2022, they announced the goal of doubling this to $8 billion by COP27 (AIM for Climate 2022).

Several innovation priorities and emerging solutions would help reduce emissions:

1. Alternative proteins

Livestock and their feed contribute about 60 percent of emissions from the food system and take up a majority of agricultural land (Xu et al. 2021). Alternative proteins—to replace or reduce meat, dairy, and eggs from ruminants and other livestock in the human diet—could be a particularly high-leverage way to reduce emissions in agriculture. Alternative proteins can be sourced from plants, insects, fungi, or through tissue culture, and many efforts to develop alternatives are underway. Plant-based meat, milk, and eggs have been on the market in high-income countries for several years, although their market share is still small. Cultivated meat, which is meat produced by in vitro cultures of animal cells, is still being developed, with several leading companies transitioning to pilot-scale facilities that will manufacture the first wave of commercialized products following regulatory approval (GFI 2021). It's not clear, however, how financially viable cultivated meat will be for widespread adoption. Currently, most plant-based proteins are more expensive than their animal-based counterparts. Accelerating research and development of these options so that some reach price parity with animal-based meat and achieve equivalent consumer acceptance is therefore essential.

2. Reducing food loss and waste

About one-third of food is lost or wasted between the farm and the fork. Improved harvesting techniques, through mechanization, can help prevent food loss on fields. Limited refrigeration and food processing in developing countries leads to large storage losses, yet innovative storage systems, such as evaporative coolers or solar-powered cold storage, provide technical options to reduce handling and storage losses. Evaporative coolers can be constructed from locally available materials and do not require elaborate training, but agricultural extension services will be needed to help spread awareness of their potential to preserve food, and limited availability of water may prevent their uptake.

Fruits and vegetables are commonly wasted. One promising technology to address this is the emergence of inexpensive methods that slow the ripening of produce. Companies are already investigating a variety of natural compounds to do this. Thin spray-on films that inhibit bacterial growth and retain water in fruit can prevent spoilage (Searchinger et al. 2019a).

3. Crop and livestock breeding

Crop and livestock breeding have the potential to improve yields and increase resilience to climate change. Crop breeding has driven much of the world's previous yield gains; although, in the past, breeding efforts have focused on a select few crops. It will be important for breeding research to expand into crops (including local varieties) that historically have been ignored in breeding efforts (e.g., sorghum, millet, potatoes, peas, cassava, and beans), which are key crops in sub-Saharan Africa (Searchinger et al. 2019b). Innovations in breeding and genetic engineering show potential to deliver crop and livestock varieties that provide more resilience to climate extremes, as well as higher yields and in some cases (such as rice) lower emissions. Barriers to farmers and ranchers adopting new varieties of crops and livestock include lack of finance and lack of reliable information on their benefits (Jack 2013).

4. Reducing methane emissions from livestock

For reducing methane from ruminants, the largest source of emissions from agricultural production (48 percent of the total in 2019), two lines of innovation are being widely explored: breeding low-methane ruminants and developing feed additives to reduce emissions. A recent report by CGIAR examined peer-reviewed research on 10 feed additives and found that 2 additives routinely delivered over a 20 percent reduction of enteric methane. However, the report notes that more research is needed to be confident that any of the 10 additives also improve the production of meat and dairy (Hegarty et al. 2021). Similarly, in New Zealand, 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). Developing breeds of livestock or crop varieties that produce fewer greenhouse gas emissions has the advantage of not requiring farmers or ranchers to change their behavior.

5. Reducing emissions from fertilizers (synthetic and manure)

Soil fertilization using synthetic fertilizers and manure represents 13 percent of direct emissions from agriculture, and manure left on pastures accounts for another 13 percent. Nitrous oxide emissions can be significantly reduced in many places by reducing the use of fertilizer, which leads to water pollution and nitrous oxide

emissions. Innovations to address this include precision application of fertilizers using field productivity data from drones or satellites. Controlled-release fertilizers, which slowly release nutrients over time, have been commercialized but currently represent only a small share of synthetic fertilizer sales. Uncertainty among farmers about their benefits, and lack of research into scaling up use of these fertilizers, may be contributing factors (Searchinger et al. 2019b).

Synthetic fertilizers cause emissions of carbon dioxide in their production, but there is potential to reduce the CO_2 emissions by replacing natural gas with low-carbon or renewable hydrogen in the production process. The fertilizer sector represents an important early opportunity to expand the use of low-carbon and renewable hydrogen, helping to bring down its costs and enable its use in a broader range of sectors (green hydrogen is further discussed in Section 4).

Manure is an alternative to synthetic fertilizers that is filled with the carbon and nutrients absorbed originally by plants and eaten and digested by animals. Manure is used for fertilizer in many places; however, global manure supply is not enough to substitute the scale and nutrient composition of current fertilizer demand. In addition, manure management practices are needed to prevent air and water pollution. Separating wet and solid manure can help reduce emissions, and exporting manure to agricultural operations that need it can help avoid overapplication.

Nitrification inhibitors can reduce nitrogen losses and increase the amount of nitrogen taken up by plants, leading to lower greenhouse gas emissions. Although several nitrification inhibitors are widely used in agriculture, their benefits depend on the environmental conditions and the rate of fertilizer application (Norton and Ouyang 2019). Nitrification inhibitors are still costly, and without a regulatory push, research into such technologies has stagnated (Searchinger et al. 2019b).

6. Agroecological approaches

According to the IPCC, agroecological approaches can improve climate resilience and bring multiple co-benefits (IPCC 2022b). These practices include agroforestry, silvopasture, crop and livestock diversification, cover cropping, crop rotations, and improved grazing practices.

Agroforestry is any form of farming in which farmers deliberately integrate woody plants—trees and shrubs—with crops or livestock on the same land. This term refers to systems with tree crops, such as rubber or cocoa, systems that incorporate trees into row crop agriculture, or those that incorporate trees on pastures (also known as silvopasture). Agroforestry can contribute to climate adaptation by reducing soil erosion, improving soil carbon content, and improving water retention (Dinesh 2017), but more research is needed into the carbon mitigation potential of agroforestry systems. Well-managed agroforestry systems can enhance crop yields and provide other co-benefits. For example, in Niger and Zambia, incorporating the tree species *Faidherbia albida* into row-cropping improved grain yields several years in a row. Trees can also provide shade, nuts, medicines, and fiber—all important for direct human use (Searchinger et al. 2019b).

Agroforestry systems may not be appropriate for all climates and soil types, and better context-specific information on benefits of these systems would help farmers understand the costs and benefits. Barriers to adoption of agroforestry also include costs of inputs, increased labor requirements, and lack of land tenure (Kouassi et al. 2021). In addition, some countries' forest codes still contain provisions that allow forest service agents to impose fines or otherwise discourage farmers from investing in protecting or regenerating trees in agroforestry systems (Searchinger et al. 2019b).

More research will be needed to evaluate the context-specific costs, benefits, and mitigation potential of agroforestry projects and share that information systematically through agricultural extension services or digital services.

As noted in the latest IPCC report, some agroecological approaches could reduce yields: "[Agroecology] that incorporates management practices used in organic farming may result in reduced yields, driving compensatory agricultural production elsewhere" (IPCC 2022b). A number of studies (e.g., Bossio et al. 2020) explore the potential to sequester additional carbon in soils and vegetation in working agricultural lands (e.g., croplands and grasslands) and thereby reduce net agricultural emissions, but more research is needed into approaches that could improve land-based carbon stocks over the long term, while also maintaining or boosting yields. Other innovative approaches that could reduce emissions or improve soil and water management include water harvesting, alternative wetting and drying of rice paddies, and precision application of fertilizers.

7. Digital services

Digitalization is a powerful emerging instrument that can help farmers adapt and improve resilience to climate change and that can support small-scale producers (Ferdinand et al. 2021; Dinesh 2017). Improved climate forecasts and pest and disease early warning systems can give farmers and ranchers vital information to support productivity. The number of digital services, such as advisory services, early warning systems, digital finance, and smart farming services, has increased rapidly in lower- and middle-income countries in the past decade, although in some countries their uptake is limited by poor access to electricity and wireless networks (IFPRI 2022).

As of 2018, 33 million farms in Africa had registered for digital climate-informed advisory services—around 13 percent of all sub-Saharan African smallholders (Tsan et al. 2019). Despite the recent increase in registration for these services, an estimated 300 million small-scale agricultural producers globally still lack access. The Global Commission on Adaptation estimates that expanding the reach and quality of these digital services will require governments and the private sector to invest approximately $7 billion over the next decade. Approximately $1 billion has been invested in digital climate-informed advisory services in the last five years, so an exponential push in investment from both public and private sector actors is needed (Ferdinand et al. 2021). According to the IPCC (2019), "The most effective early warning systems are not simply technical systems of information dissemination, but utilise and develop community capacities, create local ownership of the system, and are based on a shared understanding of needs and purpose."

SECTION 8

Technological Carbon Removal

TABLE 11 | Summary of global progress toward technological carbon removal target

INDICATOR	MOST RECENT DATA POINT (YEAR)	2030 TARGET	2050 TARGET	TRAJECTORY OF CHANGE	ACCELERATION FACTOR	STATUS
Technological carbon removal ($MtCO_2$/yr)	0.54 (2020)	75	4,500		>10x	

Note: $MtCO_2$/yr = million tonnes of carbon dioxide per year. Due to limited data, the linear trendline for this indicator was calculated using four years of data, rather than five years.

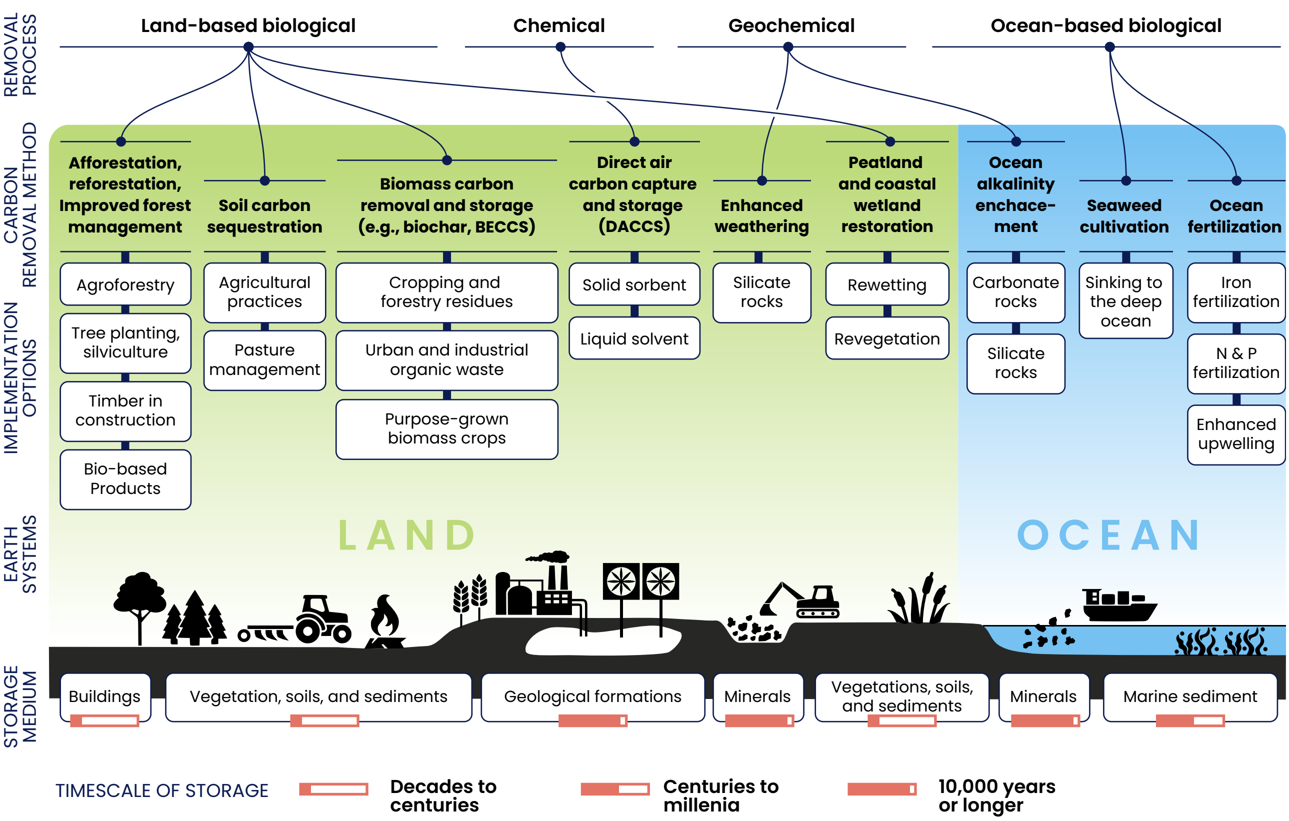
Sources: Historical data based on U.S. EPA (2021), Climeworks (2021), and Höglund (2022); targets based on IPCC (2018) and Fuss et al. (2018).

All pathways that limit warming to 1.5°C rely on carbon dioxide removal (referred to hereafter as carbon removal), including nature-based approaches and carbon removal technologies, as a complement to deep emissions reductions (IPCC 2022b). Near-term emissions reductions are a top priority, but carbon removal will also be needed to meet global climate goals.

Carbon removal is needed to remove excess CO_2 in the atmosphere to stay within the limited carbon budget available for keeping temperature rise to 1.5°C. It can counterbalance residual GHG emissions for which abatement technologies do not become available or are not cost-effective at scale (e.g., long-haul aviation, some heavy industry, non-CO_2 emissions from agriculture) (Honegger et al. 2021; IPCC 2022b). In the longer term, carbon removal will be needed to reduce atmospheric CO_2 concentrations closer to preindustrial levels.

The amount of carbon removal ultimately required to avoid the worst impacts of climate change 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. Climate modeling scenarios analyzed by the IPCC show a wide range of reliance on carbon removal technologies, from less than 1 $GtCO_2$ per year to more than 14 $GtCO_2$ in 2050 (requiring a massive scale-up from today's levels; Table 11) (IPCC 2022b). However, the IPCC's assessment includes some scenarios

FIGURE 67 | Range of carbon removal approaches on land and in the ocean



Notes: BECCS = bioenergy with carbon capture and storage; N&P = nitrogen and phosphorus..

Source: IPCC (2022b).

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).

Carbon removal includes a range of approaches, from nature-based approaches like reforestation, peatland rewetting, and mangrove restoration (Forests and Land Indicators 2, 4, and 6) to technological approaches like direct air capture (DAC), mineralization, and biomass carbon removal and storage (Figure 67, Box 7) (NASEM 2019). 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). And they all include trade-offs that will need to be evaluated on a local basis.

Developing a robust portfolio of approaches will be critical to reducing costs, minimizing risks, and balancing the trade-offs associated with any one solution (Mulligan et al. 2020). A portfolio that includes only nature-based approaches could face uncertainty around permanence and land area constraints, while a technology-specific portfolio would be more costly and

BOX 7 | Technological readiness and barriers to scale-up of key carbon removal technologies

The following technological carbon removal approaches are included in 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 (e.g., mineralization) include permanent sequestration.

- **Direct air capture:** 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 underground. There have been two dominant DAC technologies since the first plant in 2010. In recent years, a new generation of DAC companies has emerged with variations on the existing system types as well as entirely new technologies that could significantly reduce energy input, and thus costs. There are 18 DAC plants globally, with the largest one removing 0.004 $MtCO_2$/yr, powered by geothermal energy in Iceland (Climeworks 2021; IEA 2022a); construction of a new plant designed to capture 0.036 $MtCO_2$/yr broke ground in June 2022 (Climeworks 2022a). A 1 $MtCO_2$/yr plant is also expected to come online in late 2024 in the United States (BNEF 2021d). High cost, in part due to energy needs, is a key barrier to more rapid scale-up (NASEM 2019; Lackner and Azarabadi 2021); tonnes of CO_2 removed by DAC have sold for from around \$300/tCO_2 to more than \$2,000/tCO_2 on voluntary markets (Höglund 2022).
- **Biomass carbon removal and storage (BiCRS):** BiCRS is the dominant carbon removal approach using biomass, but few BiCRS projects exist globally despite a long history of use in energy system models (Fuss and Johnsson 2021). Other conceptions of biomass usage, including biomass gasification to hydrogen with carbon sequestration, have been proposed, but only a few projects exist (for example, the company Charm Industrial injects bio-oil into the ground for permanent sequestration of embodied carbon). Biochar converts biomass to a stable form that can also be used as a soil amendment. 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. Access to nearby sites for permanent geologic sequestration will also be needed for pathways that require storage of captured CO_2 (NASEM 2019). Biomass-based carbon removal approaches have sold for \$100/tCO_2 to more than \$600/tCO_2 on voluntary markets (Höglund 2022).
- **Mineralization:** Mineralization includes processes that accelerate natural rock weathering processes that take up carbon dioxide. A handful of pilot projects using mineralization exist, and several companies have launched in recent years that use various iterations of mineralization—on croplands, coastal areas, and in the ocean. For example, large-scale testing is underway on mineralization on croplands, which also provides co-benefits like added nutrients and reduced soil erosion (Copman 2021). Further research will be needed to identify optimal application parameters (mineral type, location, particle size, etc.), understand ecological and environmental impacts (especially for ocean-based approaches), and develop robust monitoring and verification approaches (Sandalow et al. 2021). Mineralization-based carbon removal has sold for \$75/tCO_2 up to more than \$1,300/tCO_2 on voluntary markets (Höglund 2022).

lack many of the co-benefits that natural approaches 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); some ocean-based approaches have large theoretical potential but many ecological and governance uncertainties.

Status of the technological carbon removal indicator

TECHNOLOGICAL CARBON REMOVAL INDICATOR 1:

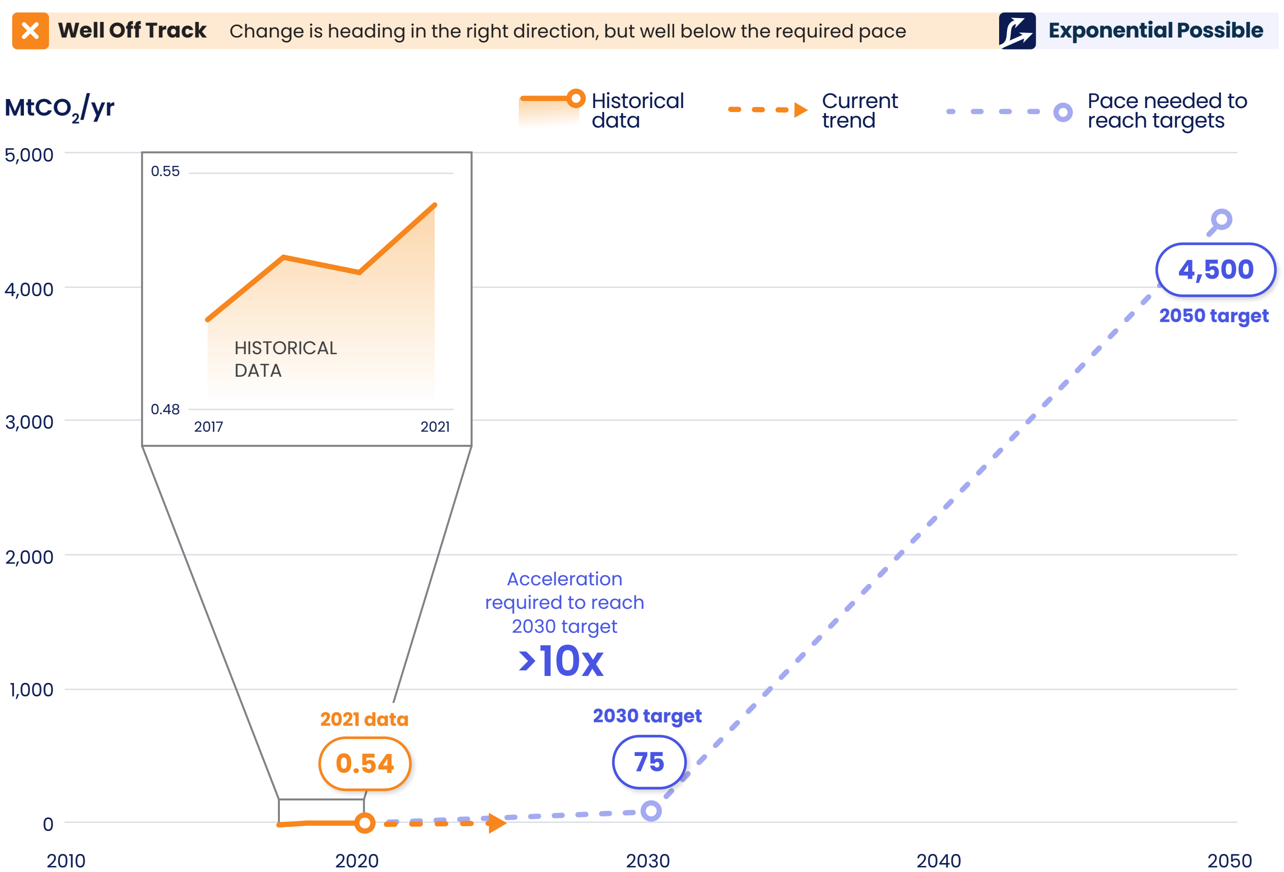
Technological carbon removal ($MtCO_2$/yr)

- **Target**: The annual rate of technological carbon removal reaches 75 $MtCO_2$/yr by 2030 and 4,500 $MtCO_2$/yr by 2050.[67]

A key indicator for tracking progress on carbon removal is identifying how many tonnes of CO_2 have been captured from the air through technological carbon removal approaches and stored permanently. 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 (this would be emissions reduction rather than carbon removal since it is preventing emissions from entering the atmosphere). Then it must be permanently sequestered through storage in deep underground geological formations, the creation of stable carbonate minerals, or use in durable products.

Today less than 1 $MtCO_2$/yr comes from technological carbon removal. DAC capacity is around 0.008 $MtCO_2$/yr (IEA 2022a), 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 Climeworks, a Swiss company. For biomass carbon removal, one ethanol facility with carbon capture and storage, located in the U.S. state of Illinois, stored 0.52 $MtCO_2$/yr in 2020, the latest year of data available (U.S. EPA 2021); the only other facility of its kind permanently sequestering CO_2 became operational in July 2022 in North Dakota (Anchondo 2022). Purchases through voluntary carbon markets indicate an additional 0.019 $MtCO_2$ were delivered in 2020 through voluntary purchases of DAC, mineralization,

FIGURE 68 | Historical progress toward 2030 and 2050 targets for technological carbon removal



Notes: $MtCO_2$/yr = million tonnes of carbon dioxide per year. Due to data limitations, the linear trendline for this indicator was calculated using four years of data, rather than five years.

Sources: Historical data based on U.S. EPA (2021), Climeworks (2021), and Höglund (2022); targets based on IPCC (2018) and Fuss et al. (2018).

and biomass-based approaches (Höglund 2022), but data are incomplete and include only what is reported publicly. This comes to an estimated 0.54 $MtCO_2$ in 2020, or less than 1 percent of the amount of carbon removal expected to be needed by 2030 (Figure 68).[68] The historical rate of change would need to accelerate more than 10-fold to meet the 2030 target.

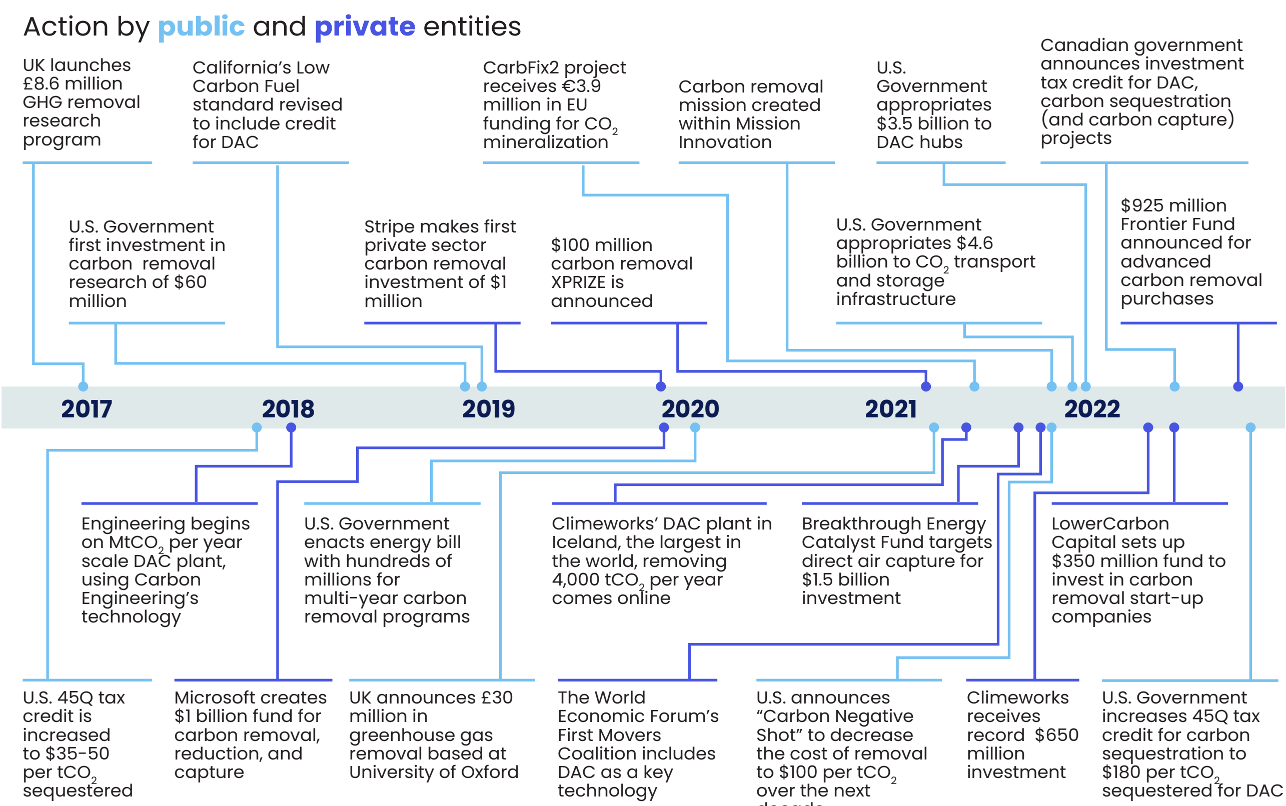
If some of the current barriers to uptake of technological carbon removal are overcome, the growth trajectory may become less linear and more like an S-curve.[69] Even though the number of tonnes removed today is small and all carbon removal technologies remain in the emergence phase—such that this indicator is categorized as well off track—the momentum needed to drive change is rapidly accelerating in terms of commitments and investment.

Global assessment of progress for technological carbon removal

Interest and investment in carbon removal technologies has grown significantly over the past few years, especially following the IPCC's *Special Report on Global Warming of 1.5°C* in 2018, and reaffirmed more recently by the IPCC's Sixth Assessment Report from Working Group III. Both find a need for hundreds of billions of tonnes of carbon removal by the end of the century along with deep emissions reductions (IPCC 2022b, 2018a). The 2018 report indicated the need to reach net-zero CO_2 emissions by midcentury to keep temperature rise to 1.5°C, which spurred a proliferation of national and corporate net-zero targets. The Science Based Targets initiative reports that 1,379 companies had net-zero commitments as of October 2022 (SBTi 2022); some of these companies will likely use carbon removal as one way to help meet their goals. At the national level, 24 of the 50 long-term strategies submitted to the UNFCCC as of March 2022 include plans to use technological carbon removal (Schumer and Lebling 2022; SBTi 2022). With these targets in place, many companies and countries are looking to carbon removal technologies to address emissions where abatement options do not become available or are too costly.

Momentum is increasing globally (Figure 69), as well as in a handful of leading countries, including the United States (Box 8). Carbon removal was added to the agenda for Mission Innovation—a global initiative to accelerate clean energy innovation—with the goal of achieving a net reduction of 100 $MtCO_2$/yr by 2030, the Carbon Removal XPrize is offering $100 million for scalable carbon removal technologies or approaches,

FIGURE 69 | Growing momentum around technological carbon removal



Notes: CO_2 = carbon dioxide; DAC = direct air capture; GHG = greenhouse gas; $MtCO_2$ = million tonnes of carbon dioxide; tCO_2 = tonnes of carbon dioxide.

Source: Authors' analysis.

BOX 8 | U.S. action on carbon removal

As the largest cumulative historical GHG emitter, the United States has a responsibility to lead carbon removal development to help clean up these emissions (Fyson et al. 2020). The U.S. long-term strategy outlines the need for around half a billion tonnes of domestic technological carbon removal 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 expected need. Federal investment in research has grown by more than 10-fold over the past several years (U.S. House of Representatives 2022a); a major infrastructure law recently 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; and the Department of Energy announced a "Carbon Negative Shot" initiative to reduce the price of carbon removal to $100/$tCO_2$ removed for pathways that can reach gigatonne scale (U.S. DOE 2021). As context, prices today vary by pathway, with purchasers of carbon removal tonnes paying as low as $75/$tCO_2$ for mineralization to more than $2,000/$tCO_2$ for DAC (Höglund 2022).

Legislative proposals have also been introduced to support carbon removal, for example through mandating direct government purchase of an increasing number of tonnes of carbon removal at declining prices (U.S. House of Representatives 2022b). And the Inflation Reduction Act of 2022 provides a higher level of support for DAC (U.S. Senate 2022).

The private sector is also stepping up. 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 (Microsoft 2021; CarbonPlan 2022). In April 2022, a coalition of companies including Stripe and Shopify launched the Frontier Fund, committing to purchasing $925 million in permanent carbon removal between 2022 and 2030 (Frontier 2022). This commitment helps provide the demand signal for carbon removal companies to make investments.

and more governments are supporting research, development, and demonstration (RD&D) (IEA 2022a). DAC, as one prominent carbon removal technology, has received particular attention: DAC was identified as a key sector under the World Economic Forum's First Movers Coalition, the $1.5 billion Breakthrough Energy Catalyst fund identified DAC as a key solution that will underpin a low-carbon economy, and Climeworks (2022b), a leading DAC company, raised $650 million in funding.

This level of action is far beyond anything that was happening just five years ago. Carbon removal has transformed from an idea that few people were focused on before 2018 to being well recognized as critical to achieving our climate goals and the recipient of billions of dollars in funding, with the first generation of large-scale projects planned to come online in the next several years.

At the same time, there is some concern and skepticism about this growing momentum. Some highlight the risk that carbon removal, particularly technological carbon removal, can distract from the needed focus on and investment in emissions reductions today (Grant et al. 2021; Markusson et al. 2018; 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 and water usage) that must be better understood and assessed on a project-by-project basis. As carbon removal is scaled up, it will be important to make sure the responsibilities and burdens of that transition are distributed fairly and prioritize the needs of communities already disproportionately affected by the impacts of climate change (Batres et al. 2021).

Consideration of trade-offs will be critical given the expected impacts of various carbon removal technologies. DAC, for example, uses nontrivial amounts of energy, which if powered by renewables would require lots of land area (e.g., solar panels take up more space than a natural gas plant with carbon capture, while other options like offshore wind or pairing with small, modular nuclear reactors would use less land) (Lebling et al. 2022). At the same time, DAC is expected to provide up to 3,000 jobs per Mt-scale plant, including close to 300 for ongoing plant operations and the rest related to plant investment (e.g., construction, engineering, and materials manufacturing) (Larsen et al. 2020). BECCS presents concerns related to sourcing biomass feedstocks and potential food security, biodiversity, and emissions impacts if land is dedicated to biomass production, but it also produces energy, jobs, and could help reduce wildfires by using waste biomass from forests (Cabiyo et al. 2021; Creutzig et al. 2021). Mineralization could require large-scale mining of relevant rocks and minerals, which includes trade-offs related to environmental impacts but could produce useful products like synthetic construction aggregate and provide jobs.

As technological carbon removal is a relatively new industry, ensuring that there are sufficient guardrails will be critical to building public trust and understanding, and making sure the process is credible, sustainable, and equitable (Mace et al. 2018). Guardrails, in the form of policies and governance mechanisms at the international and national levels, could include guidance around how much carbon removal can be used in company or national climate commitments relative to emissions reductions, credible and consistent monitoring and verification methods, and how to consider economic, environmental, social and equity, and other trade-offs across approaches. At a project level, consideration of environmental and social impacts will be needed alongside technoeconomic assessments to identify optimal siting location and to communicate local impacts to communities that could host the project so they can provide informed input into decision-making processes or reject hosting the project if desired (Lebling et al. 2022; Kosar et al. 2021). Engaging with potential host communities early and providing opportunities for input on project configuration and negotiation of community benefits (e.g., local job guarantees, investment in job training and apprenticeships) will be critical to building community support and the project's long-term success.

Enabling conditions for climate action across technological carbon removal

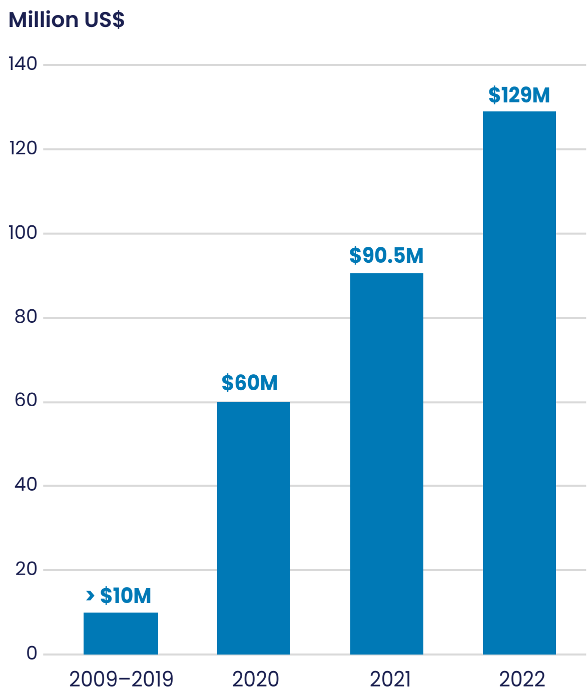
Carbon removal technologies are at different stages of development, with approaches like mineralization largely in research and pilot testing, while some variations of DAC are further along, with a few large-scale projects in progress. While none have reached widespread market adoption, progress has been made in recent years, particularly around direct air capture. Yet barriers to accelerating the scale-up of carbon removal technologies include high cost, insufficient enabling infrastructure (e.g., geologic sequestration), insufficient demand for carbon removal in part because it is largely a public good, lack of comprehensive governance frameworks, and lack of broad public support for large-scale carbon removal (NASEM 2019; Amador et al. 2021). In the longer term, determining who will pay for large-scale carbon removal—across the public and private sectors—will need to be addressed as well (ETC 2022; McCormick 2022).

Scale up government funding for RD&D

Government investment in RD&D is needed to develop a wide range of new carbon removal technologies, as well as to further optimize the ones we have today and reduce costs. Developing a diverse portfolio of carbon removal technologies will be critical to minimizing risks associated with any one approach and reducing overall costs (Mulligan et al. 2020). A handful of countries have started funding or increased the amount of federal funding going toward development of carbon removal technologies, including Australia, Canada, Japan, the United Kingdom, and the United States (IEA 2022a).

For example, federal RD&D investment in the United States grew significantly over the past few years (Figure 70). In May 2021, the United Kingdom also announced £30 million for research into a suite of natural and technological greenhouse gas removal approaches to help reach the country's net-zero target by 2050 (UKRI 2021). And the European Union is providing funding for carbon removal, with a goal of 5 $MtCO_2$/yr removed via carbon removal technologies by 2030 (EU 2021a, 2021b).

FIGURE 70 | U.S. federal funding for RD&D for carbon removal technologies



Notes: RD&D = Research, development, and demonstration. This chart only includes carbon removal RD&D funding to the U.S. Department of Energy through annual appropriations; additional funding for direct air capture came through the Bipartisan Infrastructure Law including $3.5 billion over five years for DAC hubs and $115 million for DAC technology prizes.

Sources: U.S. House of Representatives (2020, 2021a, 2021b, 2022a).

Increase policies for deployment support

Government support for deployment will also be needed since carbon removal technologies are costly and not yet commercialized. Deployment support can come through a variety of channels such as investment or production tax credits, loans, grants, tax-advantaged financing structures, government procurement of products made with captured CO_2, or direct government procurement of carbon removal, among others (Capanna et al. 2021). The government has a role to play here, along with supporting other types of climate action, because carbon removal is a public good rather than a product that people need to purchase, so opportunities for direct revenue are limited. Governments in developed economies also have a particular responsibility given their historical role in contributing to excess concentrations in the atmosphere (Fyson et al. 2020). At the same time, the private sector also will need to play a role, and is already doing so.

In the United States, which is currently a leader in carbon removal investment, the 45Q tax credit is the most important deployment support: the Inflation Reduction Act of 2022 increased the credit value to \$130–\$180/tCO_2 sequestered via DAC, up from \$35–\$50/tCO_2 since 2018. Additionally, the U.S. state of California's Low-Carbon Fuel Standard was revised in 2019 to include DAC, which provides a credit of nearly \$100/tCO_2 for DAC development anywhere (Neste 2022). The two credits can be combined to provide substantial support for the development of emerging carbon removal technologies.

The Canadian government also announced, in April 2022, an investment tax credit for carbon removal from the air, carbon capture, and geologic sequestration at 60 percent, 50 percent, and 37.5 percent of the investment cost, respectively, which is a substantial incentive for companies looking to capture and sequester carbon dioxide (Scherer 2022).

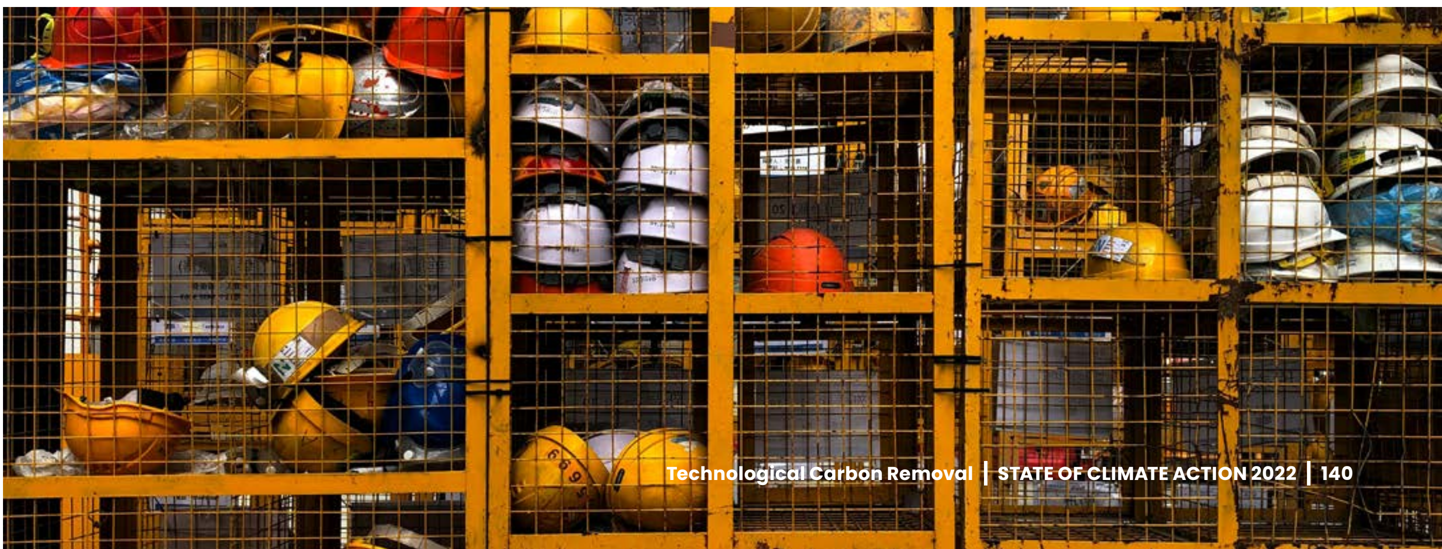
Broader policies like carbon pricing (Finance Indicator 5) would also support carbon removal scale-up and partially address the question of who is responsible for paying for carbon removal in the long term.

Expand enabling infrastructure

Enabling infrastructure, such as geologic sequestration facilities, CO_2 transport infrastructure, and abundant renewable and zero-carbon energy to power carbon removal technologies will all be needed to enable their scale-up. CO_2 pipelines, or transport infrastructure by rail, barge, or other means, would be needed where CO_2 is captured in a different location from sequestration or use and would be relevant for DAC and BECCS. Global geologic sequestration capacity is estimated to be on the order of thousands of billions of tonnes (Kearns et al. 2017), but further work will be needed for site-specific characterization. For CO_2 pipelines, there are 5,200 miles in the United States (U.S. CEQ 2021), where the vast majority of global CO_2 transport happens today. Estimates suggest 30,000–65,000 miles are needed in the United States alone—with the total also dependent on the amount of point source carbon capture and storage deployed for mitigation purposes (Abramson et al. 2020; Larson et al. 2021).

Many carbon removal technologies will also need to be powered by renewable or zero-carbon electricity and heat. Since renewable power will be needed to decarbonize the grid and to electrify other sectors like buildings and transport, energy capacity for carbon removal would need to be additional to expansion needed for other sectors, implying an even faster need for renewable scale-up.

As with DAC plants, siting these types of enabling infrastructure will require consideration of not just technical and economic factors but also environmental and social impacts to ensure that they are not overburdening communities disproportionately affected by climate change and that communities that choose to host projects have opportunities to access information about potential local impacts, provide input on projects to the extent possible, and negotiate for local benefits like jobs.



Make corporate investments and credible commitments

Along with federal investment, the private sector will need to play a role in investing in carbon removal technologies, and it is already beginning to do so. As an increasing number of companies make net-zero pledges (1,379 companies as of October 2022), they may rely on carbon removal technologies, along with deep emissions reductions, to meet those targets (SBTi 2022).

Some companies and organizations have already started buying or putting in advance orders for tonnes of carbon removal. Data here are not complete, but from those publicly available, around $55 million has gone toward purchasing tonnes of carbon removal since 2020 (Höglund 2022). Private capital through investment funds is also increasingly flowing to carbon removal. For example, Lowercarbon Capital raised $350 million to invest in carbon removal start-ups, and Bill Gates's Catalyst fund aims to mobilize $15 billion for advancing four technologies, including direct air capture (Sacca 2022; Breakthrough Energy 2022).

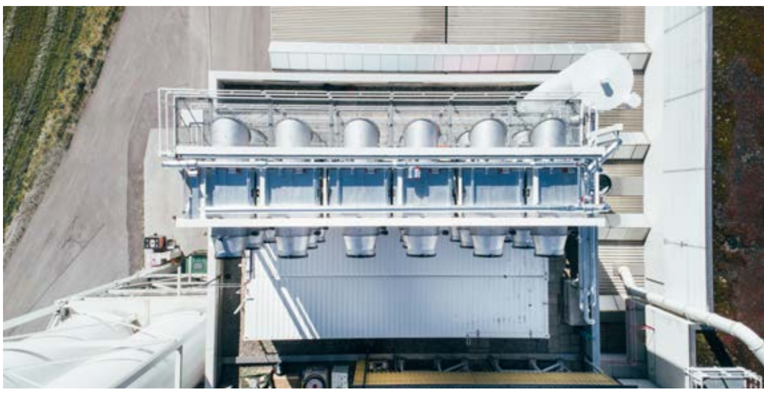
Ensuring that corporate commitments don't result in an overreliance on carbon removal rather than emissions reduction will be critical to the credibility of these pledges. Some guidance is already in place for corporate commitments. For example, the Science Based Targets initiative released its first corporate net-zero guidance in late 2021, indicating that most companies must reduce 90 percent or more of their direct emissions on the way to net zero and use carbon removal only for the remaining 5–10 percent (SBTi 2021).

Ensure robust governance and regulatory frameworks

As interest and investment in carbon removal technologies grow, regulations and governance structures will also need to be created and strengthened to ensure that the industry is scaled in a sustainable and equitable manner (Mace et al. 2018). Doing so would also help increase public acceptance and support for the technologies. Scaling equitably and sustainably requires an understanding of the risks, trade-offs, and potential benefits of each approach to help facilitate scale-up in such a way that the burden of carbon removal on people and the environment and its potential benefits are equitably distributed (Batres et al. 2021). Improving existing governance frameworks could include a range of public and private sector interventions at many levels (e.g., international, national, state, project). Here are a few examples:

- **National governments** can include stipulations around community engagement, environmental and social impact considerations, and consideration of equity as a prerequisite to project developers receiving federal funding (Lebling et al. 2022; Allen et al. 2022). Governments can also set guidance regarding relative levels of emission reduction versus carbon removal.
- **National and subnational governments** can ensure that existing zoning and infrastructure planning regulations are sufficient to regulate new carbon removal technologies and related infrastructure and that they do not concentrate locally unwanted land uses near marginalized communities (Lebling et al. 2022).
- **International organizations** can strengthen existing data and inventory systems, ensure that accounting rules are robust, strengthen international cooperation, and create incentives for and engage with the carbon removal research community (Mace et al. 2018).
- **Private sector**: Purchasers of carbon removal and platforms that can certify and sell carbon removal credits for voluntary markets can include sustainability, community engagement, and other relevant stipulations for credits to be bought or sold as high-quality options. Project developers can use community benefit agreements 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.
- **Civil society organizations**: Nongovernmental organizations, academia, and other types of organizations can provide accountability for government and private sector action and advocate for marginalized communities and for transparency in decision-making processes.

Governments, the private sector, and civil society will all need to work together to strengthen these frameworks as the industry takes off.



SECTION 9

Finance

Transforming power, buildings, industry, trans-port, forests and land, and food and agriculture, as well as scaling up carbon removal technologies, all will require significant increases and shifts in finance, as well as a broader transformation of the financial system, to be aligned with climate goals (IPCC 2022b). The global financial system is a major underwriter of GHG emissions and carbon lock-in, with many of the world's leading financial institutions investing in fossil fuels, commodities that drive deforestation, and other activities that will put the Paris Agreement's 1.5°C temperature limit out of reach. Through their investments, both public and private financial institutions have an outsized impact, whether positive or negative, on the transition to a net-zero world.

Transforming the global financial system to support ambitious climate action entails scaling up climate finance, both public and private; measuring, reporting, and managing climate risks; properly accounting for the full cost of GHG emissions through carbon pricing mechanisms; and ending public financing for fossil fuels. While recent rates of change across these critical shifts are all heading in the right direction, they remain well below the pace required (Table 12).

TABLE 12 | Summary of global progress toward finance targets

INDICATOR	MOST RECENT DATA POINT (YEAR)	2030 TARGET	2050 TARGET	TRAJECTORY OF CHANGE	ACCELERATION FACTOR	STATUS
Global total climate finance (trillion US$/yr)	0.6 (2020)	5.2	5.1	↗	>10x	✕
Global public climate finance (trillion $/yr)	0.30 (2020)	1.31–2.61	1.29–2.57	↗	>10x	✕
Global private climate finance (trillion $/yr)	0.34 (2020)	2.61–3.92	2.57–3.86	↗	>10x	✕
Share of global emissions under mandatory corporate climate risk disclosure (%)	4 (2022)	75	75	↗	>10x	✕
Median carbon price in jurisdictions with pricing systems (2015 $/t$CO_2$e)	23 (2022)	170–290	430–990	↗	8x	✕
Total public financing for fossil fuels (billion $/yr)	690 (2020)[a]	0	0	↗	5x	✕

Note: 2015 $/t$CO_2$e = 2015 dollars per tonne of carbon dioxide equivalent.

[a] Data on capital expenditure by G20 state-owned entities on fossil fuels was not available for 2020, so the 2019 figure of $250 billion is used.

Sources: Historical data from Buchner et al. (2021), Macquarie et al. (2020), Wu and Uddin (2022), Naik (2021), WRI (2022f), World Bank (2022a), OECD and IISD (2021), OCI (2022), and Geddes et al. (2020); targets from IPCC (2018, 2022b), IEA (2021h), OECD (2017), UNEP (2021e, 2021b), Climate Analytics and WRI (2021), and IPCC (2022b).

Status of finance indicators

FINANCE INDICATOR 1:

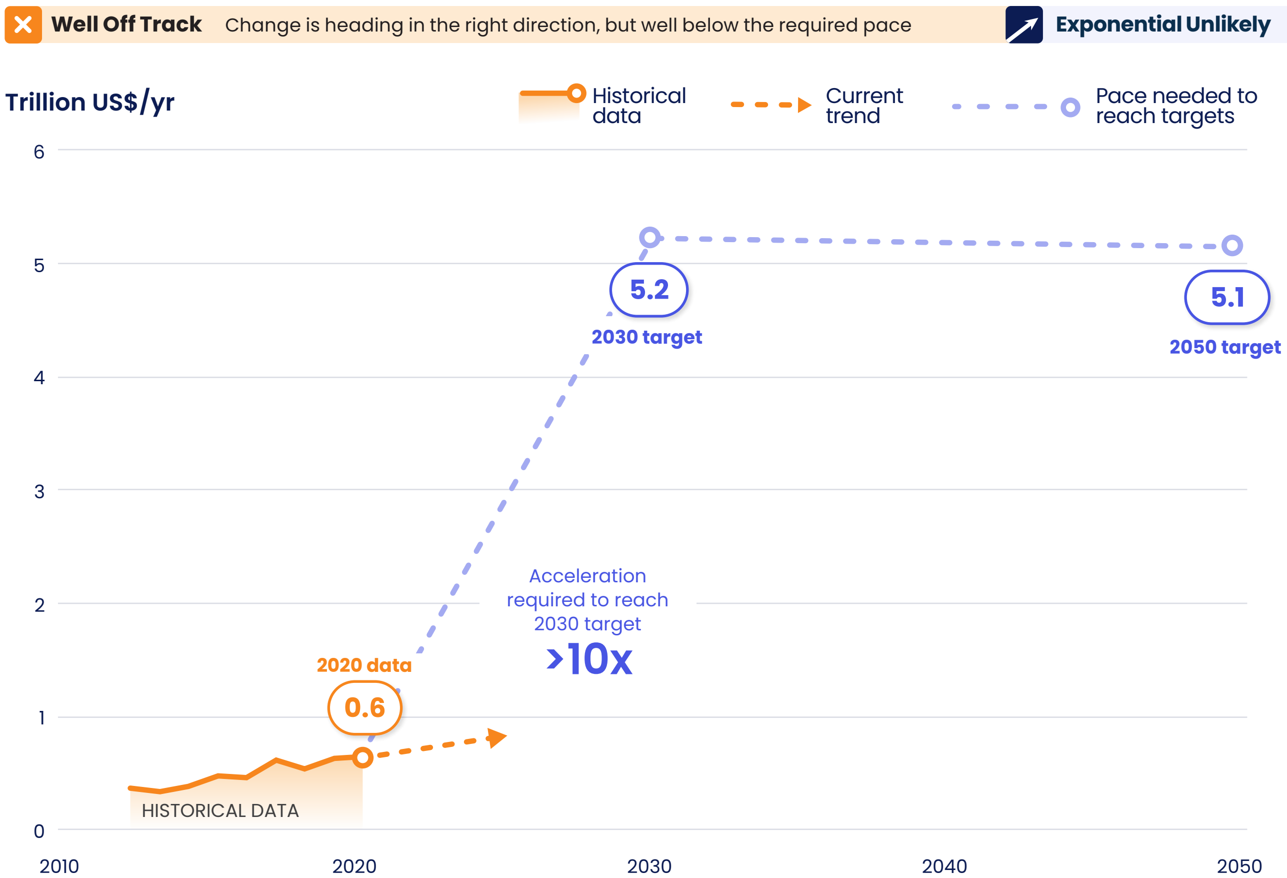
Global total climate finance (trillion $/yr)

- **Target**: 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.

Total global flows of climate finance, including both public and private, and domestic and international flows,[70] reached $640 billion in 2020 (Buchner et al. 2021), increasing by an average of $38.6 billion per year over the preceding five years.[71] By comparison, total global investment in fossil fuels was estimated at $726 billion in 2020 (IEA 2021s), 13 percent more than total tracked climate finance. Recent progress made in scaling up total climate finance, then, remains well off track, and the total amount of global climate finance would need to increase more than 8-fold to reach the near-term target of $5.2 trillion per year by 2030. This equates to an average increase of $458 billion per year between 2020 and 2030—over 10 times the historical rate of change (Figure 71).

An estimated 90 percent of global climate finance in 2019–20 ($571 billion) supported mitigation actions, and of this, over half ($334 billion) was earmarked for energy supply. Low-carbon transport saw the fastest growth in climate finance of any sector, increasing by 23 percent between 2017–18 and 2019–20 to reach $175 billion. Over three-quarters of tracked climate finance in 2019–20 originated from and was invested within the same country. Nearly half of global climate finance was invested in East Asia and the Pacific region, with 81 percent of this in China. Western Europe was the second-highest region for climate finance, followed by the United States and Canada. Collectively, these three regions accounted for 76 percent of global climate finance flows (Buchner et al. 2021).

FIGURE 71 | Historical progress toward 2030 and 2050 targets for global total climate finance (public and private, domestic and international)



Note: "Global climate finance" includes both public and private climate finance.

Sources: Historical data from Buchner et al. (2021) and Macquarie et al. (2020); targets for 2030 and 2050 based on analysis of IPCC (2018, 2022b), IEA (2021h), OECD (2017), and UNEP (2021e, 2021b).

FINANCE INDICATOR 2:

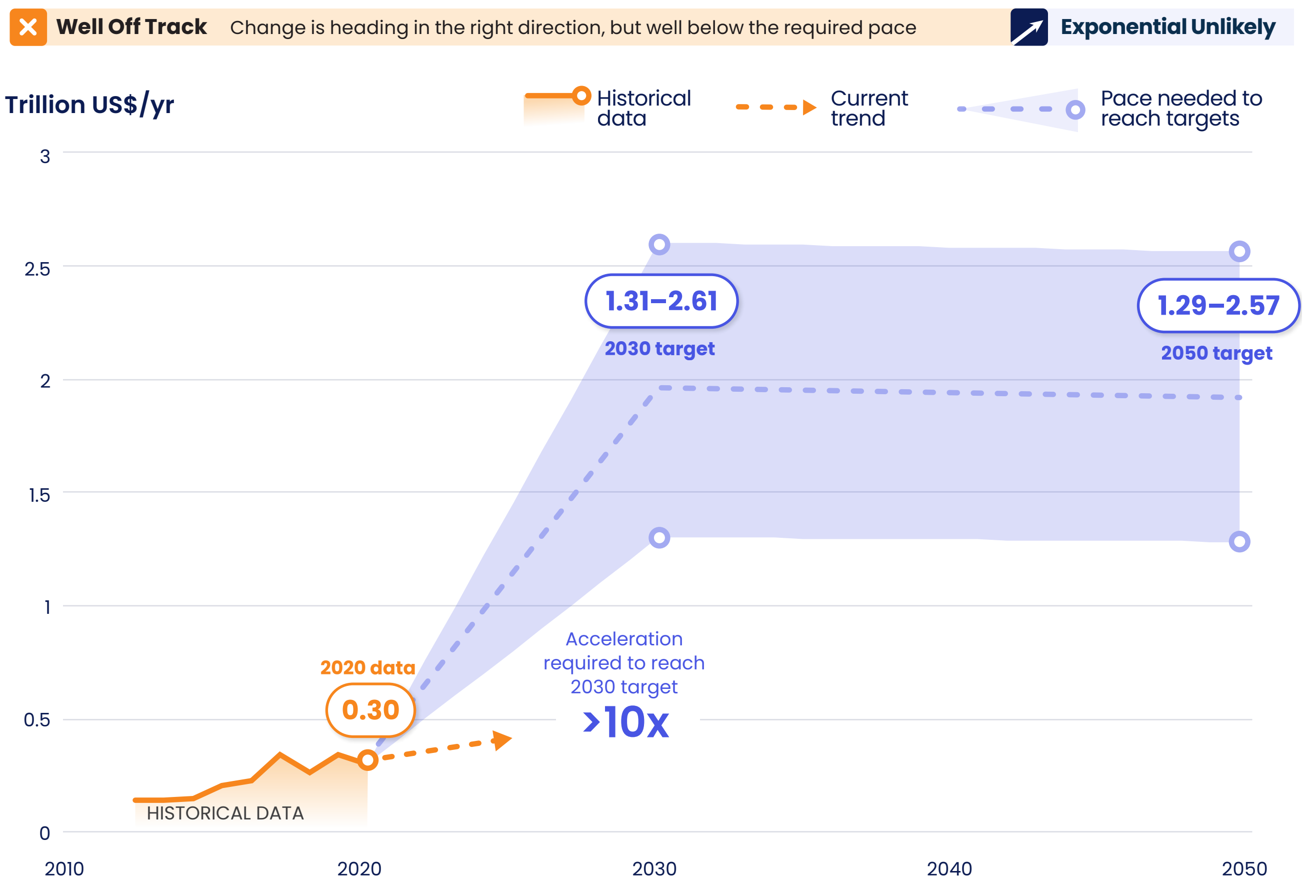
Global public climate finance (trillion $/yr)

- **Target**: Global public climate finance flows (domestic and international) reach $1.31–2.61 trillion per year by 2030 and $1.29–2.57 trillion per year by 2050.

Scaling up public finance, both domestic and international flows, is vital to ensuring a rapid transition to net-zero and resilient societies, particularly for areas where private finance is not well suited to meeting objectives at the speed and scale necessary, such as public services and infrastructure (e.g., transportation and energy networks); research, development, and deployment of new technologies; job training; and ecosystem protection. Public finance also plays a pivotal role in supporting, creating, and shaping markets, as well as 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, including by ensuring access to finance for individuals and governments who may not otherwise be able to raise resources for climate action.

Global public climate finance flows amounted to $300 billion in 2020, increasing by $15 billion per year, on average, between 2016 and 2020. However, public climate finance fell in 2020 from an all-time high of $343 billion in 2019 (Buchner et al. 2021). Based on available data,[72] recent increases in public climate finance remain well off track—the total amount of funds would need to increase more than 6-fold to reach the $2 trillion per year midpoint of the target range by 2030. This requires an average growth of $170 billion per year between 2020 and 2030—over 10 times faster than recent increases (Figure 72).

FIGURE 72 | Historical progress toward 2030 and 2050 targets for global public climate finance (domestic and international)



Sources: Historical data from Buchner et al. (2021) and Macquarie et al. (2020); targets for 2030 and 2050 based on analysis of IPCC (2018, 2022b), IEA (2021h), OECD (2017), and UNEP (2021e, 2021b).

Development finance institutions (DFIs) provided the majority of public finance in 2019–20 ($220 billion), with $120 billion coming from national DFIs and $65 billion from multilateral institutions. During the same time period, an estimated 37 percent of public climate finance flowed internationally, and 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) were invested in East Asia and Pacific ($180 billion), while sub-Saharan Africa saw the highest share from public sources, at nearly 90 percent of the region's climate finance (Buchner et al. 2021). Public climate finance flowing from developed to developing countries, specifically, reached $68.3 billion in 2020 (OECD 2022a),[73] accounting for 22 percent of total global public climate finance.

FINANCE INDICATOR 3:
Global private climate finance (trillion $/yr)

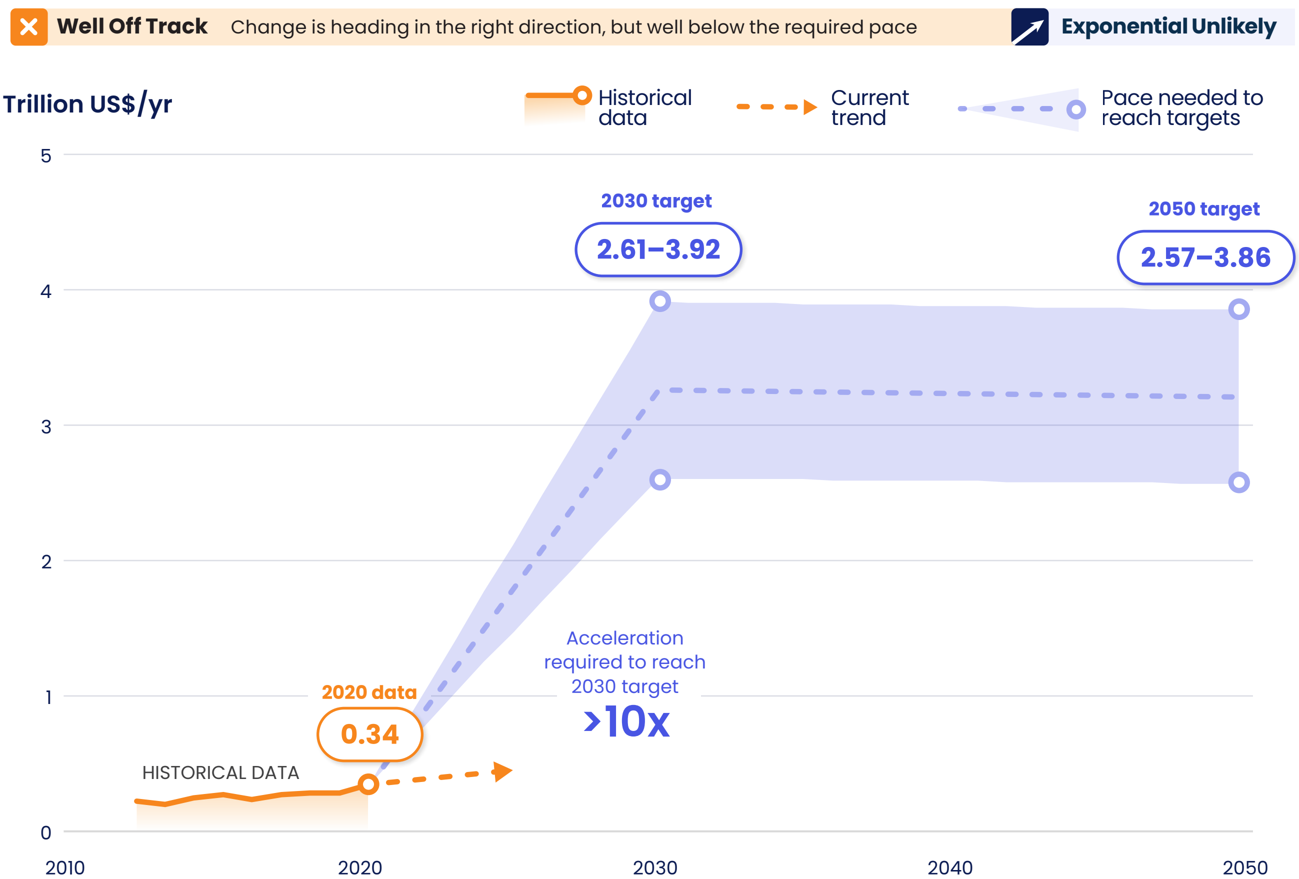
- **Target**: Global private climate finance flows (domestic and international) reach $2.61–3.92 trillion per year by 2030 and $2.57–3.86 trillion per year by 2050.

It is important to scale up private climate finance, since private finance comprises the largest share of the global economy and is not yet aligned with climate goals. Private investments in activities misaligned with the Paris Agreement will need to be scaled down; if these are then shifted toward climate objectives, it could play a substantial role in contributing to the total climate finance needed.

Global private climate finance flows from financial institutions, institutional investors, corporations, and households amounted to $340 billion in 2020,[74] growing by an average of $23 billion per year between 2016 and 2020 (Buchner et al. 2021). Although heading in the right direction, current efforts remain well off track from the 2030 and 2050 targets. The total amount of private climate finance will need to increase nearly 10-fold by 2030 to reach the $3.3 trillion per year midpoint for the target range for 2030. This requires an average growth of $290 billion more each year between 2020 and 2030, over 10 times faster than historic growth rates (Figure 73).

Corporations were the largest source 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

FIGURE 73 | Historical progress toward 2030 and 2050 targets for global private climate finance (domestic and international)



Sources: Historical data from Buchner et al. (2021) and Macquarie et al. (2020); targets for 2030 and 2050 based on analysis of IPCC (2018, 2022b), IEA (2021h), OECD (2017), and UNEP (2021e, 2021b).

private sources. A large majority of climate finance in the United States and Canada (95 percent) and Oceania (88 percent) came from private sources. In Western Europe, private sources accounted for 60 percent (Buchner et al. 2021).

FINANCE INDICATOR 4:

Share of global emissions under mandatory corporate climate risk disclosure (%)

- **Targets**: Jurisdictions representing three-quarters of global emissions mandate aligning climate risk reporting with the recommendations of the Task Force on Climate-Related Financial Disclosures (TCFD).

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 price those risks, as well as factor them into their decision-making and net-zero planning. Several countries and jurisdictions, including Brazil, the European Union, Japan, New Zealand, and the United Kingdom, have announced plans or issued proposals for mandatory climate disclosure (TCFD 2021). Most recently, the United States announced a proposal to require climate-risk disclosures for publicly traded companies (Gensler 2022), further demonstrating the growing momentum for mandatory disclosure requirements.

Most of the disclosure requirements have been based on the TCFD framework, which has become the standard framework for climate-related financial disclosures (Kröner and Newman 2021). This framework has over 2,600 supporters across 89 countries and jurisdictions, representing a combined $25 trillion in market capitalization and $194 trillion in assets under management (TCFD 2021). These numbers show significant buy-in from the largest corporations and financial institutions, but endorsements are different from actual implementation and reporting.

Disclosure on climate risks is still mostly done on a voluntary basis, with inconsistent quality that is not fully aligned with the TCFD's recommended disclosures (TCFD 2021). Governments can play a crucial role in mandating high-quality disclosures so there is universal coverage and uniformity in reporting. As of April 2022, the number of jurisdictions with mandatory climate-related disclo-

FIGURE 74 | Historical progress toward 2030 and 2050 targets for share of global emissions under mandatory corporate climate risk disclosure

Note: Countries included are France, Singapore, Japan, and the United Kingdom.

Sources: Historical data from Wu and Uddin (2022), Naik (2021), WRI (2022f), and authors' calculations. Targets for 2030 and 2050 based on analysis by Climate Analytics and WRI (2021).

sures[75] has grown to four, including France, Singapore, Japan, and the United Kingdom (Wu and Uddin 2022; Naik 2021). These countries correspond to about 4 percent of global emissions. It is expected that by the end of 2022, a total of 8 jurisdictions will have mandatory requirements, including Brazil and India, covering about 20 percent of global emissions. Although current and anticipated GHG emissions coverage remains well below the three-quarters target, it would only take a few key large-emitting countries to drastically increase the coverage of global emissions under mandatory disclosures (Figure 74). For example, China and the United States represent about 36 percent of global emissions combined (WRI 2022f), and both countries are contemplating mandatory disclosure rules, which would get coverage on track to the target.

FINANCE INDICATOR 5:

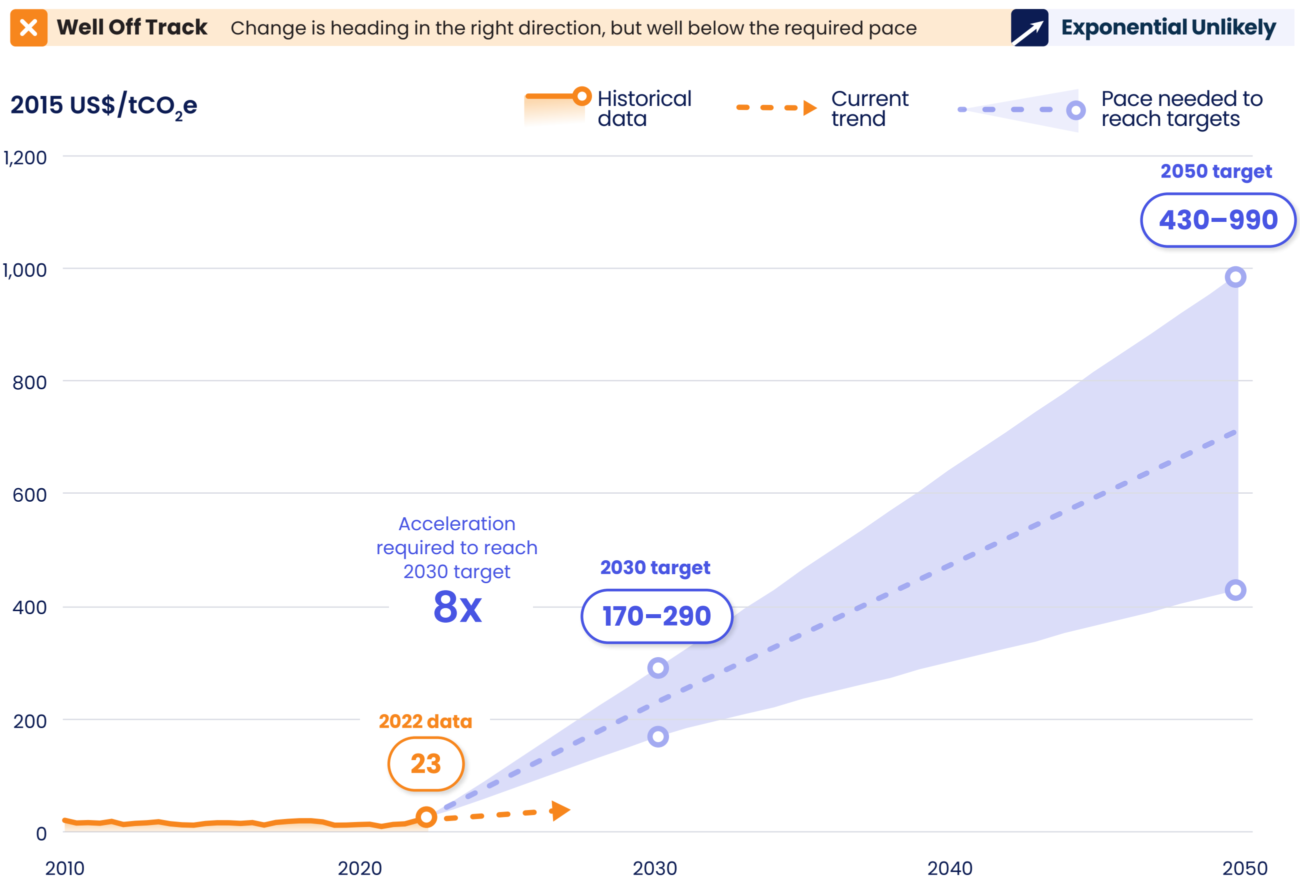
Median carbon price in jurisdictions with pricing systems (2015 $/t$CO_2$e)

- **Targets**: The median carbon price in jurisdictions with pricing systems in place reaches $170–$290/tCO_2e in 2030, and $430–$990/tCO_2e in 2050.[76]

Climate change has been called "the greatest and widest-ranging market failure ever seen" (Stern 2006), with many economists arguing that market prices do not properly account for the damages that rising GHG emissions inflict on communities around the world. Putting a sufficiently high price on carbon can send a market signal to 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 through a carbon tax or an emissions trading system (ETS) covered 23 percent of global GHG emissions in 2022, only a slight increase from the 2021 coverage of 21.5 percent (World Bank 2022b). Representing 4 percent of global emissions, 23 jurisdictions 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 countries are pricing at the minimum end of the target range of $170/t$CO_2$e required by 2030 to be consistent with a 1.5°C pathway (IPCC 2022b; World Bank 2022a). Most jurisdictions with pricing at or above the $40–$80/tCO_2e range are located in Europe, joined by only New Zealand and Uruguay outside the continent. Only Uruguay, Sweden, Liechtenstein, and Switzerland currently have carbon pricing above $100/t$CO_2$e. Uruguay is notable as a new entrant in this group

FIGURE 75 | Historical progress toward 2030 and 2050 targets for median carbon price in jurisdictions with pricing systems



Notes: 2015 $/t$CO_2$e = 2015 dollars per tonne of carbon dioxide equivalent.

Sources: Historical data adapted from World Bank (2022a); 2030 and 2050 targets based on IPCC (2022b).

of countries deploying high carbon prices and is the only developing country with carbon prices above $40/tCO_2e$ (World Bank 2022b).

Most jurisdictions with carbon pricing systems in place have lower carbon prices; the median carbon price was $23/tCO_2e$ in 2022. This increased by $3.40 per year on average between 2018 and 2022. Global progress made in increasing the median price, then, remains well off track; the median price would need to increase by roughly $26 per year—almost eight times the historical growth rate—between 2022 and 2030 to reach the target (Figure 75).

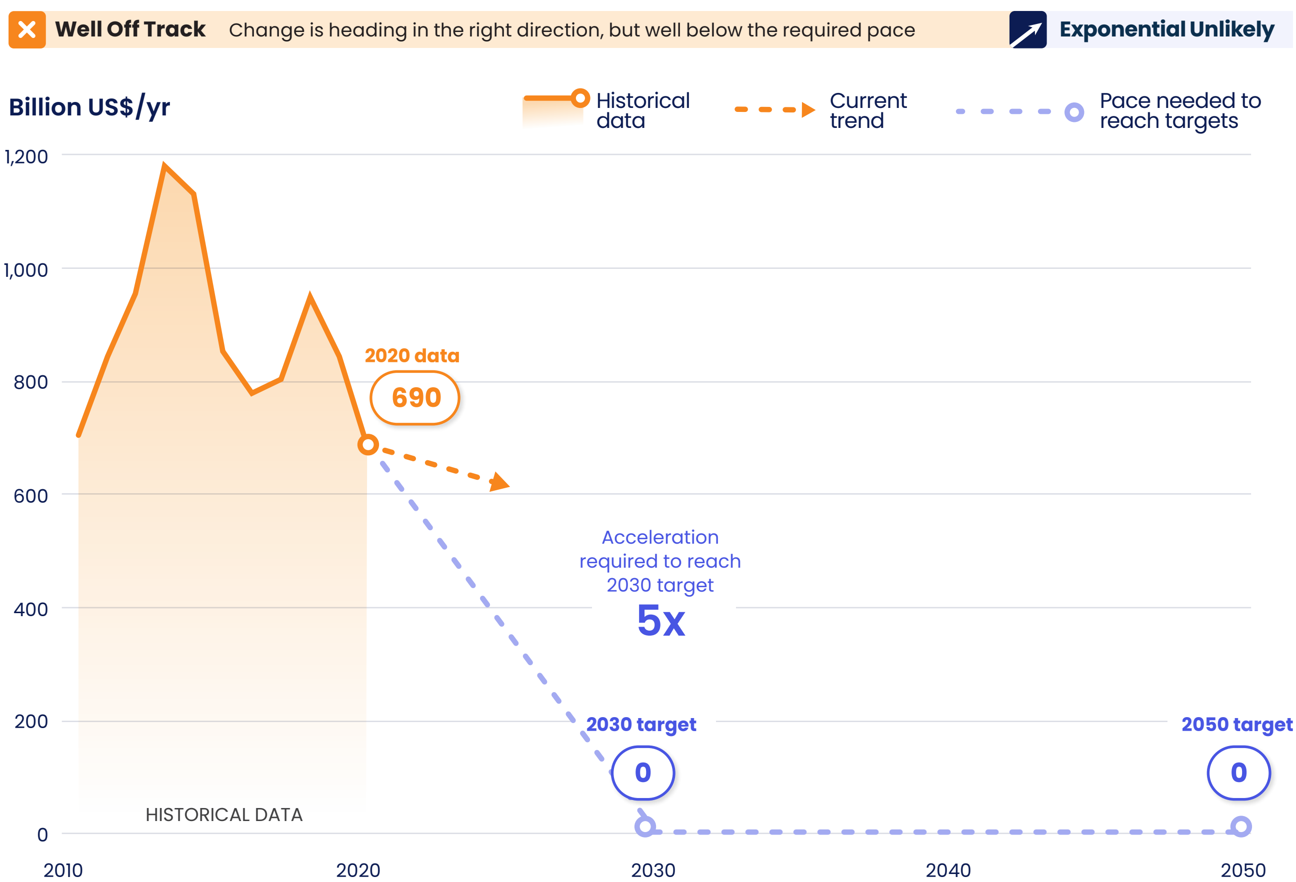
FINANCE INDICATOR 6:
Total public financing for fossil fuels (billion $/yr)

- **Targets**: Public financing for fossil fuels, including subsidies, is phased out by 2030, with G7 countries and international financial institutions achieving this by 2025.

Total public financing for fossil fuels is estimated at $690 billion in 2020. Of this total, $375 billion was production and consumption subsidies[77] (OECD and IISD 2021) and $62 billion was public financing for fossil fuel projects from multilateral development banks (MDBs), G20 countries' export credit agencies, and development finance institutions (DFIs) (OCI 2022). In addition, average capital expenditure on fossil fuels by G20 state-owned entities was $257 billion per year between 2017 and 2019, the latest data available (Geddes et al. 2020). Global public financing for fossil fuels has fallen by an average of $15 billion per year between 2016 and 2020 but needs to fall by an average of $69 billion between 2020 and 2030 to meet the 2030 phaseout target date, almost five times the historic rate of decrease. Progress toward phasing out public financing of fossil fuels globally by 2030 is therefore well off track (Figure 76).

While the pandemic and subsequent oil price crash caused consumption subsidies to drop 40 percent in 2020, there are signs they have rebounded (IEA 2022e). As economies recovered from the pandemic, governments have sought to boost fossil fuel production to meet increased demand and have increased consumption subsidies to protect households from rising energy

FIGURE 76 | Historical progress toward 2030 and 2050 targets for total public financing for fossil fuels



Note: Data are a compilation of production and consumption subsidies from 2010–20; public fossil fuel finance from multilateral development banks and G20 countries' development finance institutions and export credit agencies from 2010 to 2020; and G20 state-owned entity fossil fuel investments for 2013–19 (2019 value is used for 2020).

Sources: Historical data from OECD and IISD (2021), OCI (2022), and Geddes et al. (2020).

prices. Although global fossil fuel subsidy data for 2021 and 2022 are not yet available, fossil fuel production and consumption subsidies in 51 major economies covering 85 percent of the world's energy supply[78] nearly doubled from 2020 levels to $697 billion in 2021, 17 percent above 2019 levels (OECD 2022b). The Russian invasion of Ukraine caused energy prices to increase further, with even greater subsidies likely as governments look to develop alternative sources of supply and protect consumers from sharp price increases.

Fossil fuel capital expenditure by G20 state-owned entities has fluctuated but has not shown signs of lasting decline, and was slightly higher in 2019 than in 2013 (Geddes et al. 2020). Given the lack of 2020 data for investments in fossil fuels by state-owned entities, the most recent data available, from 2019, are used for 2020 (Geddes et al. 2020).

The only area with a clearly positive trend is fossil fuel financing by MDBs and G20 countries' public finance institutions, which has fallen by nearly half in the past five years, from a high of $119 billion in 2016 (OCI 2022). If this historical rate of decline between 2016 and 2020 ($65 billion per year) continues, public fossil fuel financing from MDBs and G20 countries' public finance institutions could reach zero by 2026.

Global assessment of progress for finance

Climate finance has risen on the global agenda in recent years. COP26 saw the launch of numerous climate finance initiatives and commitments: over 450 firms with $130 trillion in assets committed to aligning their portfolios to be net zero by 2050 (GFANZ 2021); 34 countries pledged to end their international public fossil finance by the end of 2022 and shift it into clean energy funding (COP26 Presidency 2021); and developed countries pledged to double their adaptation finance for developing countries to $40 billion per year by 2025 (UNFCCC 2021).

But the multiple other crises the world is facing—the continuing COVID-19 pandemic, the Russian invasion of Ukraine, energy and food price spikes, rising inflation, fears of an economic slowdown, and a wave of sovereign debt crises—present severe challenges to sustaining momentum on climate action in general, and climate investment in particular. Developing countries are being hit particularly hard by rising food and energy prices, increasing interest rates, and currency depreciation (United Nations 2022a, 2022b, 2022c). Less than a year since the ambitious suite of finance commitments at COP26, their delivery is facing serious headwinds.

Climate finance is growing overall, but at nowhere near the pace needed to meet investment needs, and the rate of growth has slowed in recent years (see Figure 71). Public climate finance fell in 2020, as governments shifted focus to urgent healthcare needs and social spending to deal with the COVID-19 pandemic, and fiscal stimulus to stabilize and rebuild their economies (see Figure 72). Governments largely missed the opportunity to ensure that the massive public spending in response to the pandemic was oriented toward a green recovery (UNEP 2021c). However, pandemic spending did illustrate that massive public investment in response to a crisis is possible, undermining the argument that governments do not have the money to meet climate investment needs: governments' COVID recovery spending far exceeds the amount of energy investment needed to put the world on track to 1.5°C (Andrijevic et al. 2020).

The provision of adequate financing for the poorest and most vulnerable communities is key to ensuring a just and equitable transition. This applies both within and between countries. Within countries, there is a need to ensure that effort to raise public finance is fairly shared within society, meaning that the richest individuals and companies should contribute more tax revenues. Some governments are making increased efforts to target public climate investments at disadvantaged communities that have historically borne the brunt of polluting activities as well as sectors that will be particularly affected by decarbonization. For example, the European

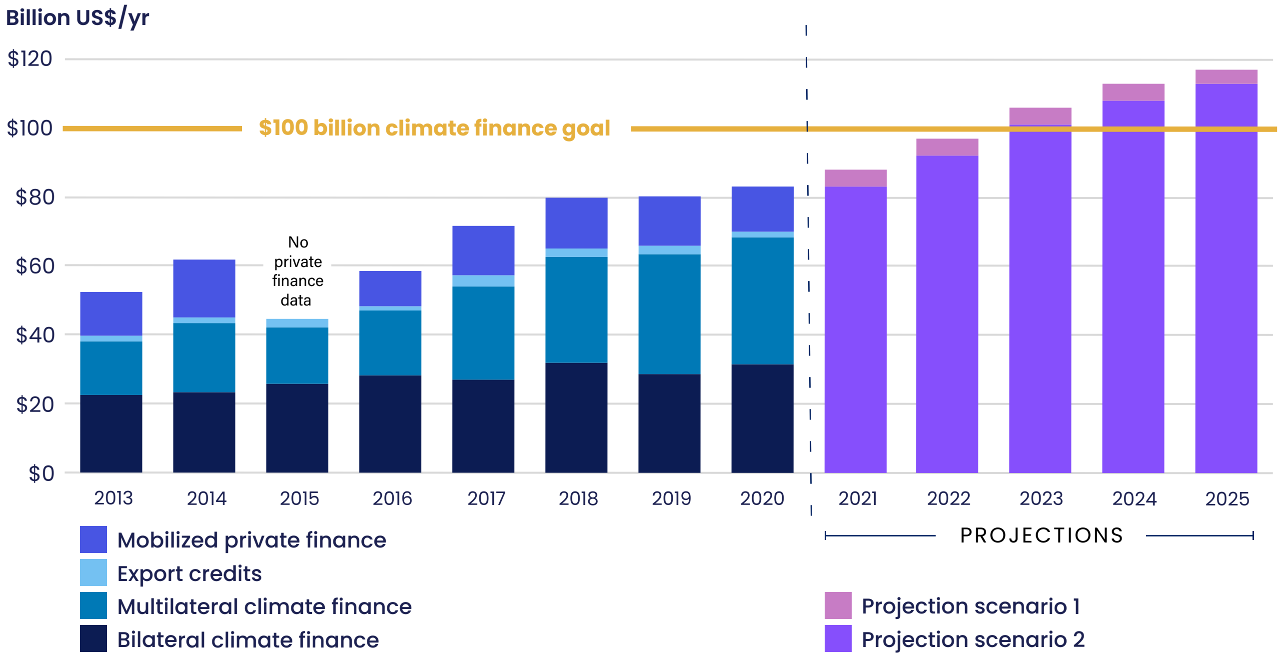
Union's Green Deal includes a Just Transition Mechanism that dedicates investment and technical support to regions and sectors most affected by the transition to carbon neutrality (WRI 2021), while in the United States the Justice40 Initiative sets a goal that 40 percent of the benefits from federal investments in climate and clean energy flow to disadvantaged communities (White House 2021). Private climate investments at minimum should not cause harm to vulnerable communities; ideally, investments should prioritize their needs.

Between countries, a core principle of the global climate regime is that the countries that have produced the greatest GHG emissions should support decarbonization and adaptation in the poorest countries, which have historically emitted little and are hit first and worst by climate change. Developed countries have an obligation under the UNFCCC and the Paris Agreement to provide climate finance for developing countries (UNFCCC 1992, 2015).

Yet developed countries have still not delivered the $100 billion per year they committed to mobilize annually for developing countries by 2020 and through 2025 (UNFCCC 2009, 2021). The OECD estimated that total climate finance from developed to developing countries reached $83.3 billion in 2020 (OECD 2022a). While the $100 billion was a collective goal by developed countries, the United States has the biggest shortfall between its climate finance provision and its fair share of the effort based on a wide variety of objective indicators, such as size of economy, cumulative GHG emissions, and population (Bos and Thwaites 2021). Developed country governments, however, 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). This requires governments to continue to scale up their climate finance in line with their pledges, yet there are concerning signs that some developed countries are cutting their international climate finance budgets, using global economic conditions and Russia's invasion of Ukraine as justifications (Lo 2022).

Phasing out public financing for fossil fuels can reduce a major driver of the climate crisis while freeing up funding for greater investment in climate solutions such as clean energy. 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). After falling to a record low in 2020 due to the drop in oil prices caused by the pandemic, the rebound in fossil fuel consumption subsidies in 2021 showed the limits of subsidy reform efforts, and that they are still largely driven by global oil prices, which rose as some countries began to emerge from pandemic shutdowns (IEA 2022e). Figure 78 shows the different sources of public fossil fuel financing. While 2022 data are not yet available, the impact of Russia's invasion of Ukraine has caused global oil prices to increase even further, which has resulted in even greater spending on fossil fuel consumption subsidies.

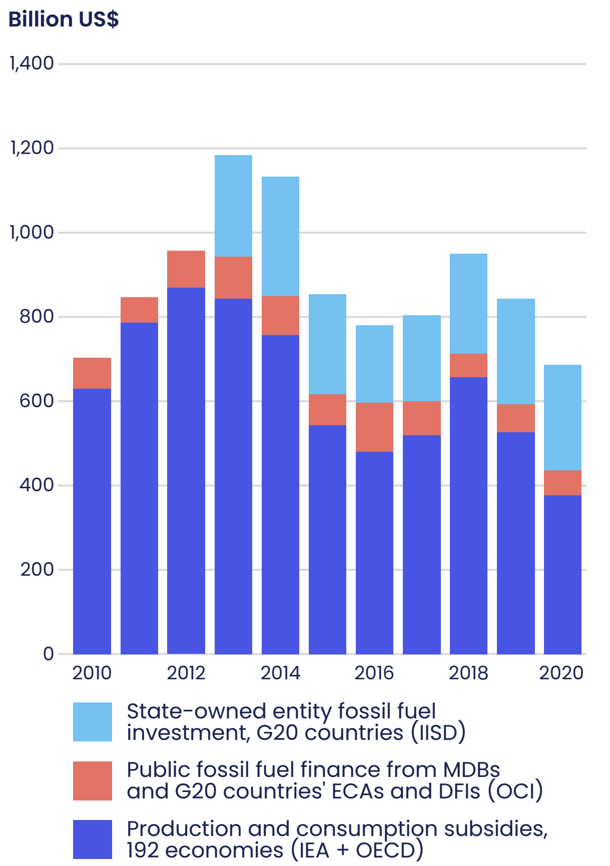
FIGURE 77 | Annual reported climate finance (2013–20) and projections (2021–25) toward the $100 billion goal



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).

FIGURE 78 | 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. Data are a compilation of production and consumption subsidies from 2010–20; public fossil fuel finance from multilateral development banks and G20 countries' development finance institutions and export credit agencies from 2010 to 2020; and G20 state-owned entity fossil fuel investments for 2013–19 (2019 value is used for 2020).

Sources: Historical data from OECD and IISD (2021), OCI (2022), and Geddes et al. (2020).

Production subsidies, however, 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 appears to have 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 2021c). Just 5.3 percent of the $18.2 trillion in total COVID-19 fiscal spending has been low-carbon, or 31.2 percent of announced recovery spending ($3.1 trillion) (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, though the clean energy finance proportion has grown compared to previous years (IISD 2022). But with the fossil fuel industry using the war in Ukraine to push for more investment in gas production and export facilities as Europe seeks to reduce dependence on Russian supply, public spending on fossil fuel production may rise again. This represents a significant opportunity cost, since such public funding could be directed to climate investments that could address inflationary pressures primarily driven by rising fuel costs (Melodia and Karlsson 2022), ensure energy access, reduce emissions, and help adapt to climate impacts.

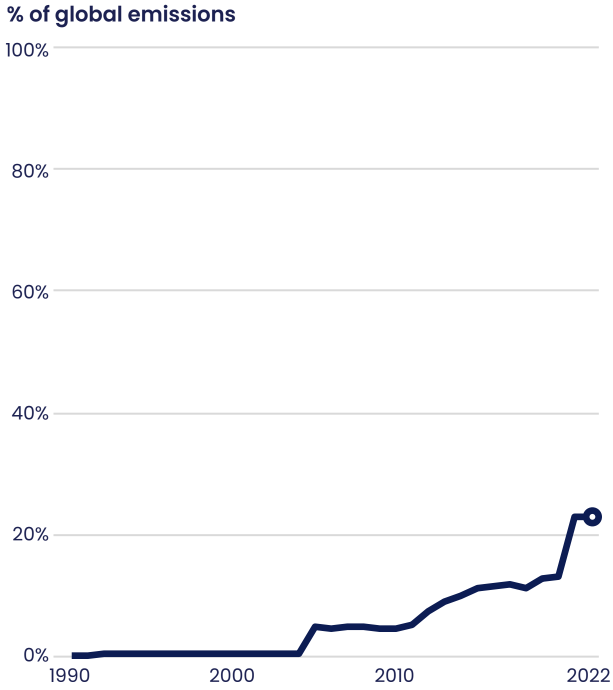
There are equity concerns that ending subsidies could hurt the poorest by making energy costs higher. However, studies across many countries have shown that richest households capture most of the benefits of fossil fuel consumption subsidies and have therefore suggested that direct cash assistance to the poorest households would be a more effective way of ensuring energy access (Coady et al. 2017). Consumption subsidy reforms need to be well managed and address concerns about impacts on the poor. 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). Another criticism has been that ending public fossil fuel financing may undermine efforts to meet SDG7, "Ensure access to affordable, reliable, sustainable and modern energy for all" (UN General Assembly 2015). However, despite international public finance for fossil fuels being more than double the amount for clean energy (OCI 2022), there is little evidence that international fossil fuel financing has effectively enhanced energy access, and the United Nations' Sustainable Energy for All concluded that "financing of fossil fuel projects as a means of closing the energy access gap should be terminated" (SEforAll and CPI 2020).

The COP26 commitment signed by 34 countries and 5 financial institutions 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) is a strong example of the multiple potential benefits of shifting finance away from fossil fuels. The signatory countries and institutions currently provide an estimated $28 billion per year in public fossil fuel finance (Dufour et al. 2022). In May 2022, G7 climate, energy, and environment ministers adopted a near-identical commitment (G7 2022a), which brings Japan, the only G7 member that had not signed onto the COP26 commitment, on board, and increases total fossil fuel financing covered to $39 billion per year (Dufour et al. 2022). Phasing out this support would accelerate progress toward ending public fossil fuel finance, and if signatories honor the commitment and shift this financing into clean energy, it would provide a noticeable boost to public climate finance and, by extension, global climate finance. Such clean energy financing flowing from developed to developing countries could also count toward the $100 billion goal, and would close the gap to meeting the $100 billion goal, a deficit that stood at $17 billion as of 2020, twice over (OECD 2022a). Despite this potential win-win, 2022 has seen signs that some signatories may be backsliding on the commitment, with the 2022 G7 leaders' summit communiqué leaving the door open to public investment in natural gas as a temporary response to the energy supply crisis resulting from the Russian invasion of Ukraine (G7 2022b). To get back on course, signatories to these commitments need to provide more details about their plans for fossil fuel finance phaseout and clean energy finance scale-up, including new or strengthened policies, and clear definitions of the criteria for any short-term exemptions (Dufour et al. 2022).

Private climate finance has grown more slowly than public climate finance over the past five years (Figure 73). Despite much rhetoric about the private sector being an essential source of climate investment, it provided just $40 billion (13 percent) more climate finance than the public sector in 2020. The Glasgow Financial Alliance for Net Zero (GFANZ) commitment by institutions to align their $130 trillion in assets to be net zero by 2050 is notable for its size and potential (GFANZ 2021), but its ambition is not yet manifesting in near-term capital shifts that will be necessary to achieve a net-zero world; annual private climate finance flows amount to less than 0.5 percent of the total assets behind the GFANZ commitment. There are questions about how the $130 trillion figure was derived, since it is larger than the total capitalization of all the world's stock markets, and likely double-counts assets along chains of lending (Lex 2021).

Comprehensive disclosure of climate-related risks by the corporate sector is one of the key steps to align private and public finance with climate goals. Governments around the world are increasingly willing to adopt mandatory climate-related disclosures in their regulatory and supervisory frameworks, with overall positive support from civil society and to a lesser extent, the business sector. Opposing political interests are likely to challenge regulations that mandate climate disclosures (especially in the United States), but there is a rising consensus from the business and financial community that a requirement for standardized reporting will be a positive and helpful development that reduces regulatory uncertainty and improves the quantity and quality of climate data that companies and investors disclose (Meager 2021). Although the quality and comprehensiveness of reporting have improved over time, they still vary considerably depending on the recommendation (TCFD 2021). Greater standardization of reporting will provide clarity and

FIGURE 79 | Share of global emissions covered by a carbon price

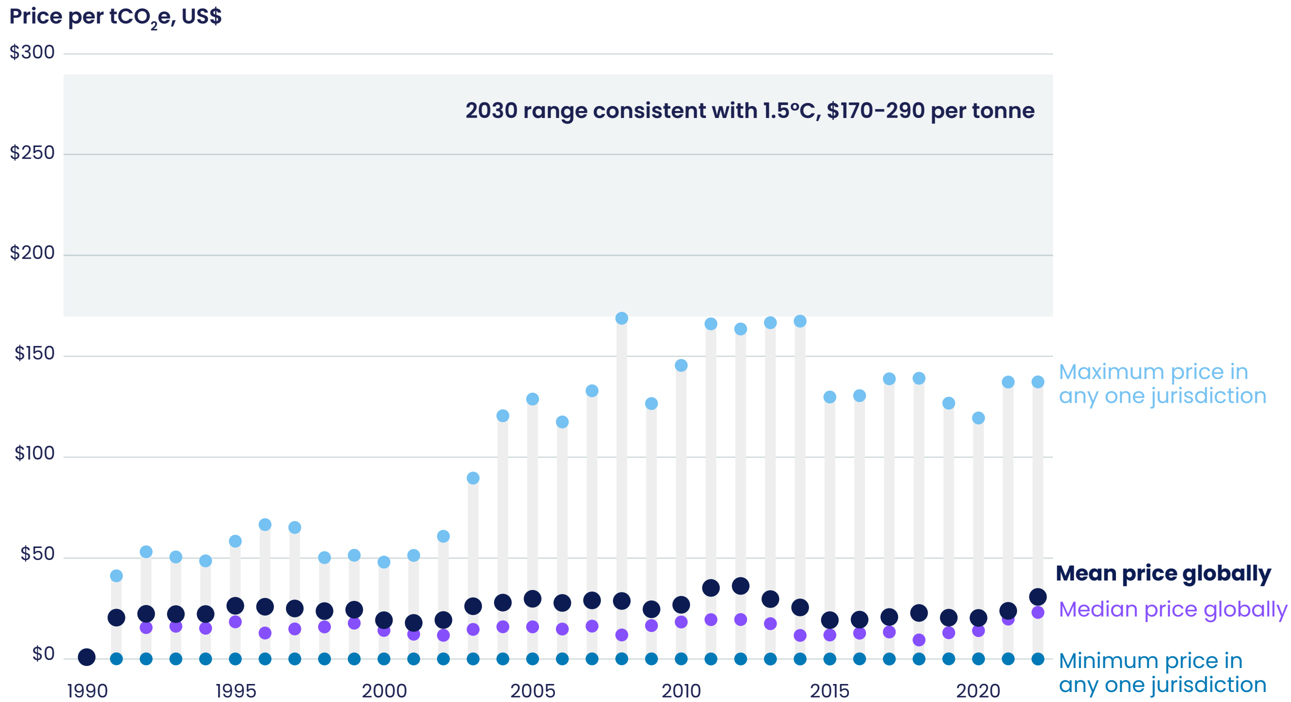


Source: Historical data adapted from World Bank (2022a).

guidance for corporations, as well as equip financial institutions and regulators with the data they need to correctly assess and manage risks, including systemic risk.

Wider adoption of carbon pricing has the potential to increase revenues that could be used to help increase public finance, while also sending market signals that can drive increased private climate investment and a shift away from fossil fuels. An estimated 46 countries and 36 subnational jurisdictions have implemented carbon pricing initiatives as of April 2022, covering 23.1 percent of global GHG emissions, as shown in Figure 79 (World Bank 2022a). This is only a slight increase from the 2021 coverage of 22.9 percent (World Bank 2022b). Just 0.2 percent of the increase in global emissions covered by carbon pricing systems between 2021 and 2022 was due to new carbon pricing mechanisms coming into effect; the remainder was due to changes in GHG emission estimates for jurisdictions already covered by pricing (World Bank 2022b). This contrasts with the large increase in emissions covered by carbon pricing between 2020 and 2021, due to China's launch of a national ETS that covers its power industry, bringing 4.5 $GtCO_2e$ (8.8 percent of global emissions) under a pricing regime. By comparison, pricing schemes in the United States, the world's second-largest annual greenhouse gas emitter after China, cover just 474 $MtCO_2e$ (0.8 percent of global emissions) (World Bank 2022a).

FIGURE 80 | Jurisdictions with carbon pricing systems in place



Notes: tCO_2e = tonne of carbon dioxide equivalent. Global mean and median price calculations are not weighted by the amount of emissions covered by each jurisdiction. Weighting would likely reduce the mean and median calculations, since the largest jurisdictions have lower prices.
Sources: Historical data adapted from World Bank (2022a); 2030 target based on IPCC (2022b).

In jurisdictions with carbon pricing systems in place, prices are insufficient—sometimes due to design issues such as overallocation of permits—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 (IPCC 2022b) (Figure 80). Carbon pricing provided $84 billion in revenues in 2021, a significant increase of over $30 billion compared to 2020 income due to higher carbon prices and the launch of new pricing systems in a number of countries (World Bank 2022b). There are equity concerns with carbon pricing, such as 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 spending on climate investments, can help increase acceptability and minimize regressive impacts (IPCC 2022b).

Enabling conditions for climate action across finance

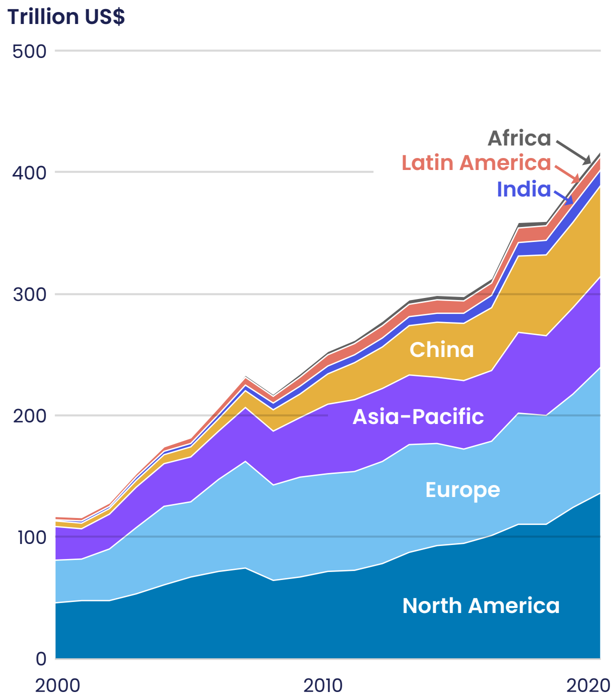
While climate finance is growing and the financial system is beginning to realign to support net-zero objectives, major barriers remain: capital continues to be misallocated toward high-emissions activities, vested interests oppose reforms to direct investments away from fossil fuels and toward clean energy, and institutional rules can prohibit governments from investing in

climate solutions and regulating finance. In this section, we identify enabling conditions that can allow governments and businesses to overcome these barriers.

Set ambitious climate finance targets and implement finance reforms

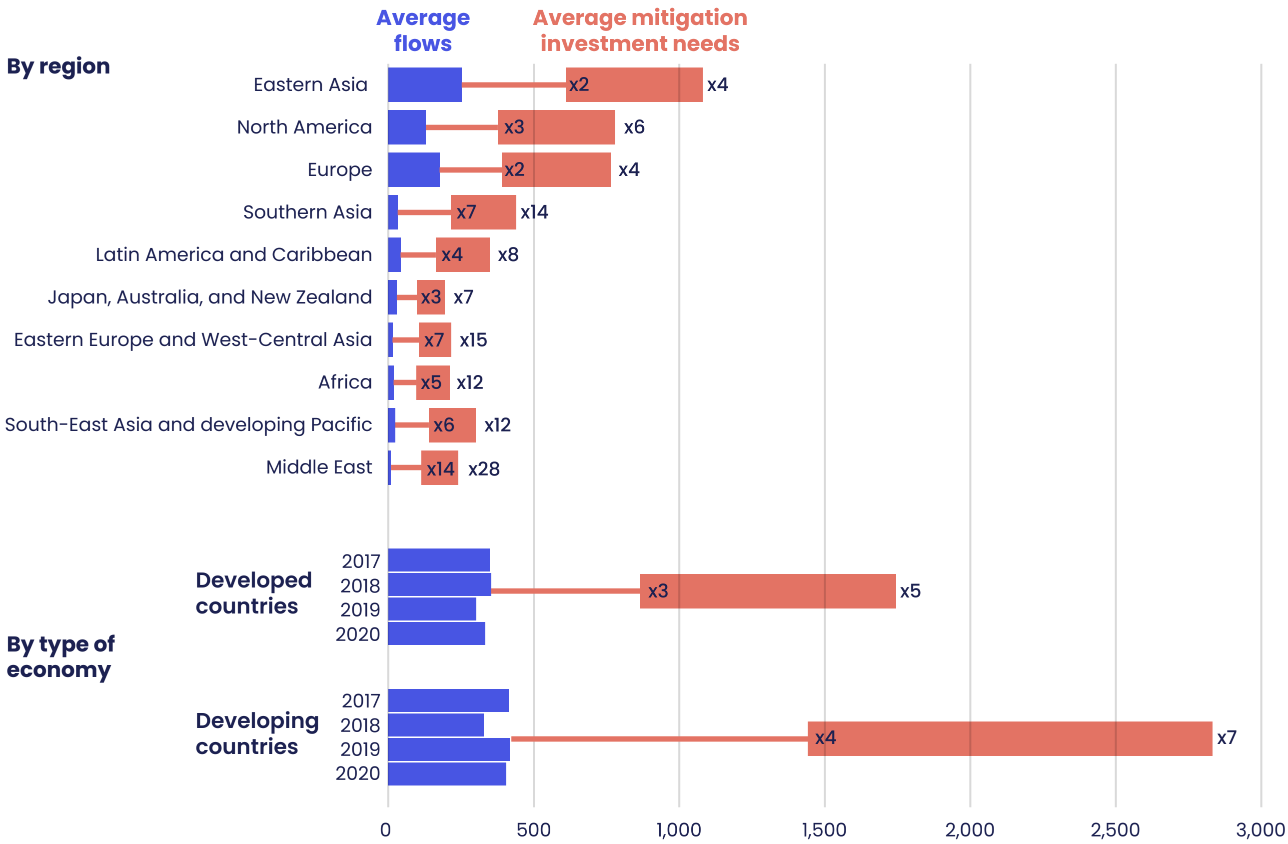
When it comes to finance, the key barrier is not a shortage of funds but rather how they are allocated (IPCC 2022b). Capital is concentrated in the hands of relatively few individuals and entities, who are currently misallocating it to high-emissions activities. This misallocation of capital, both between and within countries, has helped lock in emissions trajectories incompatible with 1.5°C. Climate investment needs for mitigation are far greater in developing countries than in developed countries (Figure 81), yet the majority of wealth is located in richer nations (Figure 82), and developing countries face significant constraints in raising both public and private investment (see subsection on strong institutions, below). Even aside from government efforts, the 10 richest men in the world own six times more wealth than the bottom 40 percent of the world's population (Ahmed et al. 2022), and these resources could be used to meet urgent climate investment needs. The wealthy bear the greatest

FIGURE 82 | Total household wealth by region



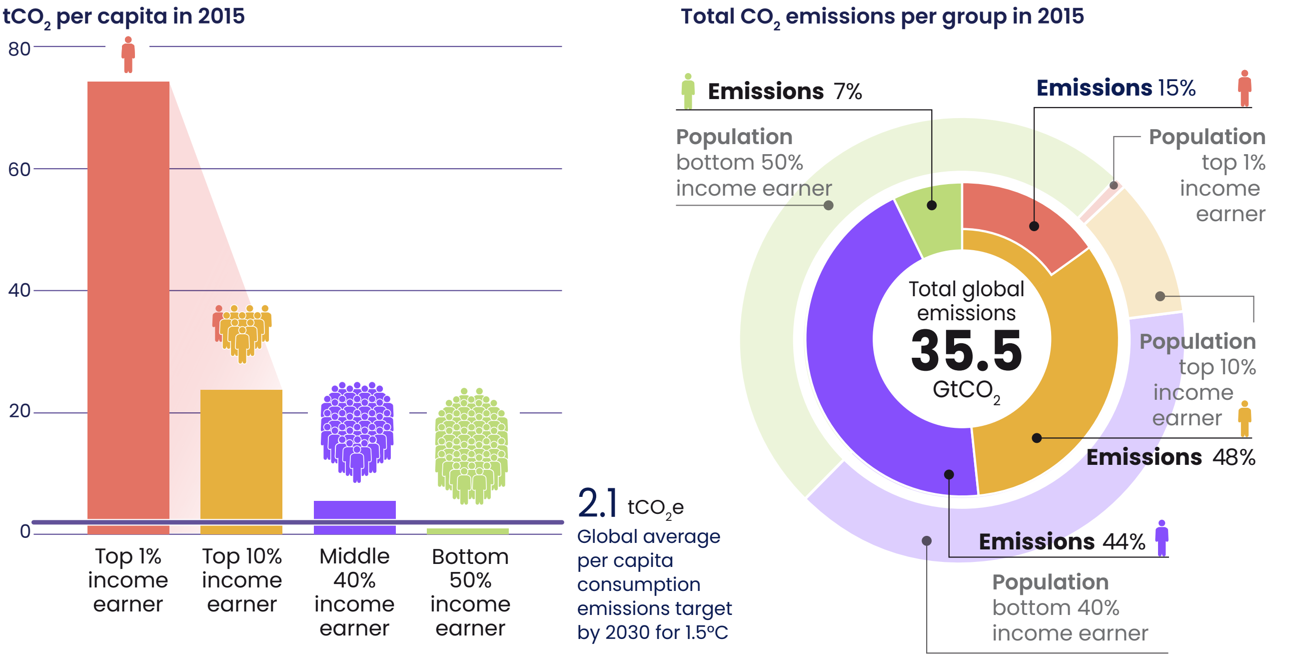
Source: Shorrocks et al. (2021).

FIGURE 81 | Breakdown of average investment flows and needs until 2030



Source: IPCC (2022b).

FIGURE 83 | 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; tCO_2e = tonnes of carbon dioxide equivalent. 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 (2020a).

responsibility for the climate crisis, with the emissions of the top 1 percent of income earners globally larger than those of the bottom 50 percent of the world's population (Figure 83) (UNEP 2020a).

The onus is therefore on those with the greatest power and wealth to show leadership by, at the very least, no longer blocking efforts to reform financial systems to be more equitable, and ideally supporting the changes to create a climate-aligned financial sector that proactively distributes power and investment to where it is most needed for climate action. Governments can increase public investments (including richer countries increasing international funding for developing countries); establish carbon pricing mechanisms that rise over time and address leakage through cooperation or border adjustment mechanisms; and phase out fossil fuel subsidies, particularly shifting production subsidies from fossil fuels to clean energy (SEI et al. 2020; Sanchez et al. 2021). Production subsidy phaseout can help reduce reliance on fossil fuels and thereby consumer sensitivity to oil prices, making phaseout of consumption subsidies politically easier. While these steps are often politically unpopular in the short term, the larger the subsidies, the more likely it is there will be civil unrest when governments can no longer afford to sustain them (McCulloch et al. 2022). Subsidy reform can pay dividends, both in terms of climate benefits and budgetary savings and in terms of reducing the likelihood of political instability. This requires political leaders to show farsighted leadership and institute well-planned and inclusive processes to phase them out.

The private sector must also show leadership by increasing its climate finance commitments—and, critically, translating them into action. The GFANZ commitment by institutions with over $130 trillion in assets to set science-aligned interim and long-term goals to reach net zero no later than 2050 (GFANZ 2021) has the potential to be a strong example of private sector leadership but requires signatory institutions to significantly shift capital allocations in the near term. To do this, climate needs to be mainstreamed into everyday decision-making throughout companies. Ensuring that company boards of directors have sufficient climate expertise and linking executive compensation to performance on climate metrics could help move climate leadership commitments from rhetoric to reality (WEF 2019).

Increase public support for financial reforms that raise revenues for climate action

One of the barriers to raising and shifting finance in line with climate goals is the perceived lack of public support for raising revenues to finance greater public spending, and for ending fossil fuel subsidies. In a climate survey by the UN Development Programme of 1.2 million people in 50 countries that represent 56 percent of the world's population, 64 percent of respondents said that climate change was an emergency and 50 percent supported governments investing more in green businesses and jobs. In 12 G20 countries, investment in green businesses and jobs enjoyed majority support. However, while increasing public investment in climate is popular, there are more mixed views about measures that can raise revenues from carbon-related taxes. Making companies pay for their pollution had just 39 percent support, although this rose to 55 percent in high-income countries (UNDP 2021). The business-as-usual scenario is for emissions to have no direct price and for fossil fuels to be heavily subsidized, so any change to this status quo feels like the addition of a new burden for those subject to pricing. Even if the benefits outweigh the costs, they are often diffused to society at large and less readily felt by individuals.

Shifting social norms around government spending can give political leaders a mandate to increase public climate finance. Current high inflation rates in many countries have increased wariness about increased government spending, but there is growing evidence that well-targeted climate investments can be deflationary in the medium to long term, since they reduce fossil fuel spending, the largest driver of contemporary inflation (Melodia and Karlsson 2022; Lewis 2020).

Changing attitudes toward increased taxation or debt financing for productive investments in climate can also help open up political space for greater public spending. Engagement and education can help to shift social norms around whether GHG emissions should be priced (Marshall et al. 2018). The use of revenues is particularly important; public support for carbon pricing is greater when some of the revenues are earmarked for investments in climate action, as has been done in Norway and Switzerland, or consumer rebates, as in the Canadian province of British Columbia and Switzerland (Baranzini and Carattini 2017; Carattini et al. 2018; Klenert et al. 2018).

Changing social norms around fossil fuel investments, such as individuals and institutions divesting their finances from fossil fuel companies, can also increase pressure on private sector actors, such as banks and asset managers, to shift financing away from fossil fuels and toward clean energy (Ansar et al. 2013).

Strengthen institutions to reduce the influence of special interests and remove barriers to climate investments

Institutional reform is an important enabler of climate action. Many climate policies enjoy broad public support, but industry opposition has been a significant impediment, with some business interests lobbying against fossil fuel subsidy reform and effective carbon pricing proposals (InfluenceMap 2020; Basseches et al. 2022).[79] While clean energy industries stand to benefit from increased investments in climate and could be expected to intervene with governments in favor of pro-climate policies, such as carbon pricing, ending fossil fuel subsidies and shifting them toward clean energy, at present their influence over policymaking does not match those of industries that are opposed to climate action (Brulle 2018).

Reforming government institutions to be more transparent, responsive, and representative can help reduce the influence of special interests, such as the fossil fuel industry, in the policymaking process, and ensure that pro-climate shifts in public opinion are better translated into durable climate policies. Countries that have created or reformed institutions to focus on climate have been able to more effectively craft and implement climate policy (Dubash 2021). For example, the United Kingdom's Climate Change Act and independent Climate Change Committee, alongside EU climate and energy governance, have helped reinforce and strengthen climate policy over time (Lockwood 2021). Conversely, in the United States the lack of institutional transformation to address climate change has led to climate policy being on a more uneven footing, oscillating as control of the executive branch has switched between parties (Mildenberger 2021). Better governance will also be important to ensure that climate finance is raised and spent equitably, responsibly, and effectively (Schalatek 2012).

International institutional structures also place barriers on increasing climate investment. For example, the International Monetary Fund (IMF) continues to recommend fiscal consolidation, which reduces governments' ability to increase public climate investment (Ray et al. 2020). Furthermore, between 2015 and 2021, the IMF recommended that over half of its member countries develop fossil fuel infrastructure (Sward et al. 2021). International financial institutions could be more accommodating of governments spending more on climate action, both through the policy advice they offer and by facilitating additional financing for poorer countries (UNCTAD 2019; Gallagher and Kozul-Wright 2019; Volz 2020). In recent years the IMF has taken steps to integrate climate considerations into its regular Article IV surveillance of member countries' economic and financial situations and has published a climate strategy that reviews its recent work to integrate climate considerations into its operations and sets out ways to deepen its engagement with countries on climate (IMF 2021b). Countries with high debt levels and/or poor credit ratings may struggle to raise additional resources through further debt issuance, and indeed climate impacts are already raising the cost of capital for vulnerable countries (Buhr et al. 2018). Debt relief and reform of international capital markets, including through mechanisms such as debt-for-climate swaps and sovereign green bonds, can improve governments' ability to raise public finance through borrowing (Volz et al. 2020; Fresnillo 2020).

Adopt policies that help increase fiscal space and address equity impacts

Lack of fiscal space available to governments is a significant constraint to increasing public climate finance, that is, their ability to raise funding either through more tax revenues, more debt issuance, or reductions in spending in other areas. A popular and equitable approach to increasing government revenues is raising taxes on wealthy individuals, who are also the greatest emitters (Figure 83), and major corporations (Newport 2019; Sawhill and Pulliam 2019; Dunn and Van Green 2021; Rowlingson et al. 2021). Table 13 outlines a variety of potential options for raising additional revenue that could be used, in part, to raise public climate finance. Efforts within the OECD and G20 to establish a global minimum corporate tax rate, which have also been backed by the G7, are estimated to raise tax revenue by between $60 billion and $100 billion a year (OECD 2021c; G7 2021). A financial transaction tax, a small levy on sales of stocks, bonds, and other financial contracts, could also raise significant funding. A globally applied financial transaction tax of 0.1 percent on shares and bonds and 0.01 percent on derivative contracts (the same rates as the European Union is considering) could raise between $237.9 billion and $418.8 billion per year (Pekanov and Schratzenstaller 2019). Carbon pricing can be a significant source of revenues: as discussed earlier, current carbon pricing revenues were $84 billion in 2021 (World Bank 2022b). The IMF estimates that a carbon tax on international transportation fuels of $75 per tonne in 2030 would raise $120 billion a year in revenue (IMF 2019). Tax increases of $0.125 per liter on gasoline and diesel and $5 per tonne on coal globally could raise $430 billion in revenues per year (Sanchez et al. 2021). Subsidy phaseout can also free up significant resources: ending consumer fossil fuel subsidies on transportation fuels and coal could raise $123 billion per year (Sanchez et al. 2021), while ending international public financing for fossil fuels would free up $62 billion a year (OCI 2022).

Regulation and economic incentives can also help address the equity impacts of emissions pricing and fossil fuel subsidy phaseout by providing protections to the poorest (Klenert et al. 2018; Zinecker et al. 2018).

TABLE 13 | Potential sources of revenue for increased public climate finance

TYPE OF REVENUE-RAISING MECHANISM	AMOUNT PER YEAR	SOURCE
Global minimum corporate tax	US$60 billion to $100 billion	OECD (2021c)
Global financial transaction tax	$238 billion to $419 billion	Pekanov and Schratzenstaller (2019)
Current carbon-pricing revenues	$84 billion	World Bank (2022b)
Carbon tax on international transportation fuels ($75/tonne)	$120 billion	IMF (2019)
Tax increase on transportation fuels ($0.125 per liter) and coal ($5/tonne)	$430 billion	Sanchez et al. (2021)
Ending consumer fossil fuel subsidies	$123 billion	Sanchez et al. (2021)
Ending international public financing for fossil fuels (G20 and MDBs)	$62 billion	OCI (2022)

Notes: G20 = group of twenty; MDB = multilateral development bank. These figures cannot simply be added together due to potential overlaps between different approaches to raising revenues (e.g., deploying carbon pricing, taxation of fuels, and reduction of fossil fuel consumption subsidies all affect fossil fuel consumption, and therefore the potential revenues that could be derived from each mechanism). Nonetheless, the figures illustrate that these mechanisms could go a significant way toward meeting public climate finance targets.

SECTION 10

Conclusion

The IPCC's Sixth Assessment Report is unequivocal: climate change endangers the well-being of both people and the planet (IPCC 2022b). Delayed action risks triggering impacts so catastrophic that our world will become unrecognizable. The next few years offer a narrow window to realize a sustainable, livable future for all. And while limiting temperature rise to 1.5°C is still possible, it will not be easy. Halving GHG emissions by 2030 and reaching net-zero CO_2 emissions around midcentury will require immediate, ambitious, and concerted action to accelerate transformational change across nearly every major system.

Yet increasingly urgent calls from the scientific community to spur rapid, far-reaching transitions have largely gone unheard. Countries' most recent national climate commitments collectively fall well short of delivering the GHG emissions cuts, as well as carbon removal, required to hold global temperature rise to 1.5°C. And of the 40 indicators assessed in this report, none have experienced a historical rate of change sufficient to meet their 1.5°C-aligned near-term target. Change is heading in the right direction, with progress unfolding at a promising, albeit insufficient pace for 6 indicators, and in the right direction, but well below the required pace for another 21 of them. For 5 indicators, rates of change are headed in the wrong direction entirely, and data are insufficient to assess progress across the remaining 8 indicators with confidence (Figure 84).

Ultimately, both international and national commitments have yet to spark the scale of progress needed to accelerate systemwide transformations aligned with a 1.5°C future. And, at the same time, addressing the climate crisis is more complex than it was a year ago. Russia's invasion of Ukraine is causing nations to rethink their food and energy strategies, as well as reshaping global collaboration. Depending on the pathway chosen, the GHG emissions gap could be reduced—as countries realize that a zero-carbon future is one that also brings energy independence and economic growth—or could be widened, as fossil fuel investments and interests are further entrenched.

However, there are promising signs that indicate accelerated change is possible. In 2021, for example, there was record growth in renewable energy installations, as well as a continuation of steep renewable energy cost reductions, particularly for solar PV. Simultaneously, electric vehicle sales soared in key markets like China, Europe, and the United States. Sustaining this momentum, however, is not guaranteed and will require additional support from governments, the private sector, and civil society. A raft of measures across all systems is also urgently needed to accelerate change across indicators that are nowhere close to achieving the required pace of change. To that end, each section of this report outlines critical factors that can enable transformational change within the system at large, ranging from innovations in technology, to policy reforms that incentivize the uptake of zero-carbon products, to behavior changes needed to shift to more sustainable lifestyles.

The years ahead offer an urgent and fleeting opportunity to avoid intensifying climate impacts, as well as additional losses and damages, by holding warming to 1.5°C. Although we are not starting from a standstill, achieving this global temperature limit will require an enormous effort from leaders across systems and around the world. The good news is that many of these actions, when implemented appropriately, can generate significant development and societal benefits—cleaner air and waterways, improved public health outcomes, and healthier ecosystems that can continue to deliver services that sustain communities around the world. And the way forward has never been clearer: together, we can seize this rapidly closing opportunity to build a better future for all. Choosing any other pathway would be unthinkable—robbing both current and future generations of their health, prosperity, and well-being.

FIGURE 84 | Summary of progress towards 2030 targets

TRAJECTORY OF CHANGE — ACCELERATION FACTOR[a]

>10x	Exponential Unlikely	
2x	Exponential Likely	
5x	Exponential Possible	

Note: We use "exponential" as shorthand for various forms of rapid, non-linear change. But not all non-linear change will be perfectly exponential.

ON TRACK: Change is occurring at or above the pace required to achieve the 2030 targets.

None

OFF TRACK: Change is heading in the right direction at a promising, but insufficient pace

6x[b]	Share of zero-carbon sources in electricity generation
1.7x	Share of electricity in the industry sector's final energy demand
5x[b]	Share of electric vehicles in light-duty vehicle sales
>10x[b]	Share of battery electric vehicles and fuel cell electric vehicles in bus sales
1.5x[c,d]	Reforestation
1.3x	Ruminant meat productivity

WELL OFF TRACK: Change is heading in the right direction, but well below the required pace

5x	Carbon intensity of electricity generation
6x	Share of unabated coal in electricity generation
5x Commercial 7x Residential	Energy intensity of building operations[e,f]
>10x	Carbon intensity of global cement production
>10x	Green hydrogen production
6x[g]	Number of kilometers of rapid transit (metro, light-rail and bus rapid transit) per 1M inhabitants (in the top 50 emitting cities)
>10x[g]	Number of kilometers of high-quality bike lanes per 1,000 inhabitants (in the top 50 emitting cities)
>10x	Share of electric vehicles in the light-duty vehicle fleet
Ins. data[b]	Share of battery electric vehicles and fuel cell electric vehicles in medium- and heavy-duty vehicle sales
Ins. data[b]	Share of sustainable aviation fuels in global aviation fuel supply
Ins. data[b]	Share of zero-emission fuel in maritime shipping fuel supply
2.5x[h]	Deforestation
6x	Crop yields
5x	Ruminant meat consumption[i]

WELL OFF TRACK: Change is heading in the right direction, but well below the required pace

>10x[j]	Technological carbon removal
>10x	Global total climate finance
>10x	Global public climate finance
>10x	Global private climate finance
>10x	Share of global emissions under mandatory corporate climate risk disclosure
8x	Median carbon price in jurisdictions with pricing systems
5x[k]	Total public financing for fossil fuels

WRONG DIRECTION: Change is heading in the wrong direction, and a U-turn is needed

N/A	Share of unabated fossil gas in electricity generation
N/A	Carbon intensity of global steel production
N/A	Share of kilometers traveled by passenger cars
N/A[c]	Mangrove loss
N/A	Agricultural production GHG emissions

INSUFFICIENT DATA: Data are insufficient to assess the gap in action required for 2030

Ins. data	Carbon intensity of building operations[f]
Ins. data	Retrofitting rate of buildings
Ins. data	Carbon intensity of land-based passenger transport
Ins. data[c]	Peatland degradation
Ins. data[c]	Peatland restoration
Ins. data[c,l]	Mangrove restoration
Ins. data	Share of food production lost
Ins. data	Food waste

FIGURE 84 | Summary of progress towards 2030 targets (continued)

Notes: GHG = greenhouse gas.

[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. In previous reports, all acceleration factors under 10 were rounded to the 10th place (e.g., 7.4), which is 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.

[b] The category of progress was adjusted for indicators categorized as exponential change likely, using methods outlined in Schumer et al. (2022), and so in these instances, the category of progress identified does not always match the acceleration factor calculated using a linear trendline. See chapters for additional information.

[c] Indicators for forests and land experience high interannual variability in historical data due to both anthropogenic and natural causes. Accordingly, we use 10 years instead of 5 years to calculate the linear trendline where possible.

[d] 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) is used to estimate the historical rate of change, rather than a linear trendline.

[e] Energy intensity is the amount of energy used per square meter of floor area, including heating, cooling, and appliances. Publicly available data report only energy intensity trends for all buildings combined, not for residential and commercial buildings separately. In calculating acceleration factors, we use this combined energy intensity trend and assume that the historical rate of change is the same for both types of buildings.

[f] This target is not global in scope, rather it focuses on reducing energy intensity in key regions and countries. See Section 3 for more details.

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

[h] Indicators for forests and land experience high interannual variability in historical data due to both anthropogenic and natural causes. Accordingly, we use 10 years instead of 5 years to calculate the linear trendline where possible. But for this indicator, we calculated a 7-year trendline using data from 2015 to 2021 due to temporal inconsistencies in the data before and after 2015 (Weisse and Potapov 2021).

[i] This target applies only to high-consuming regions, including the Americas, Europe, and Oceania.

[j] Due to limited data, the linear trendline for this indicator was calculated using four years of data, rather than five years.

[k] Data on capital expenditure by G20 state-owned entities on fossil fuels was not available for 2020, so the 2019 figure of $250 billion is used.

[l] Murray et al. (2022) estimated that 0.18 Mha of gross mangrove gain occurred from 1999 to 2019, only 8 percent of which can be attributed to direct human activities, such as mangrove restoration. Accordingly, this report does not use gross mangrove gain to approximate mangrove restoration. We estimate the most recent historical data point for mangrove restoration by taking 8% of the total gross mangrove gain from 1999-2019. See Schumer et al. (2022) for more information.

Sources: Authors' analysis based of data sources listed in each chapter.

Appendices

Appendix A

Summary of Acceleration Factors

TABLE A1 | Summary of Acceleration Factor Calculations

INDICATOR	MOST RECENT HISTORICAL DATA POINT (year)	2030 TARGET	2050 TARGET	TRAJECTORY OF CHANGE (Could this indicator experience some type of nonlinear change in the future?)	AVERAGE ANNUAL RATE OF HISTORICAL CHANGE (most recent 5 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]	EVALUATION (based on acceleration factors and, in some cases, expert judgment)
Power[b]								
Carbon intensity of electricity generation (gCO_2/kWh)	450 (2019)[c]	50–125	5–25 (2040) <0[d] (2050)		-6.9 (2015–19)	-33	5x	
Share of zero-carbon sources in electricity generation (%)	36 (2019)[c]	74–92	87–100 (2040) 98–100 (2050)		-0.74 (2015–19)	-4.2	6x	[e]
Share of unabated coal in electricity generation (%)	37 (2019)[c]	0–2.5	0 (2040) 0 (2050)		-0.52 (2015–19)	-3.2	6x	
Share of unabated fossil gas in electricity generation (%)	24 (2019)[c]	17	5 (2040) 0 (2050)		0.13 (2015–19)	-0.6	N/A; U-turn needed	
Buildings								
Energy intensity of building operations (% of 2015 levels)[f]	98 (2019)	70–80 (residential) 70–90 (commercial)	40–80 (residential) 50–85 (commercial)		-0.31 (2015–19)	-2.1 (residential) -1.6 (commercial)	7x (residential) 5x (commercial)	
Carbon intensity of building operations ($kgCO_2/m^2$)	30 (residential) 61 (commercial) (2017)	10–16 (residential) 15–21 (commercial)	0		Insufficient data	-1.3 (residential) -3.3 (commercial)	Insufficient data	
Retrofitting rate of buildings (%/yr)	<1 (2019)	2.5–3.5	3.5 (2040)		Insufficient data	0.18	Insufficient data	
Industry								
Share of electricity in the industry sector's final energy demand (%)	28 (2020)[c]	35	40–45 (2040) 50–55 (2050)		0.38 (2016–20)	0.66	1.7x	
Carbon intensity of global cement production ($kgCO_2$/t cement)	656 (2019)	360-370	55–90		-2.4 (2015–19)	-26	>10x	

TABLE A1 | Summary of Acceleration Factor Calculations (continued)

INDICATOR	MOST RECENT HISTORICAL DATA POINT (year)	2030 TARGET	2050 TARGET	TRAJECTORY OF CHANGE (Could this indicator experience some type of nonlinear change in the future?)	AVERAGE ANNUAL RATE OF HISTORICAL CHANGE (most recent 5 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]	EVALUATION (based on acceleration factors and, in some cases, expert judgment)
Industry (continued)								
Carbon intensity of global steel production (kgCO_2/t steel)	1,890 (2020)	1,335–1,350	0–130		5 (2016–20)	-55	N/A; U-turn needed	
Green hydrogen production (Mt)	0.023 (2020)	81	320		0.0035 (2016–20)	8.1	>10x	
Transport								
Share of kilometers traveled by passenger cars (%)	44 (2020)	34–44	N/A		0.86 (2015–20)	-0.45	N/A; U-turn needed[g]	
Number of kilometers of rapid transit (metro, light-rail and bus rapid transit) per 1M inhabitants (in the top 50 emitting cities) (km/1M inhabitants)	19 (2020)	38	N/A		0.34 (2015–20)	1.9	6x[g]	
Number of kilometers of high-quality bike lanes per 1,000 inhabitants (in the top 50 emitting cities) (km/1,000 inhabitants)	0.0077 (2020)	2	N/A		0.0013 (2015–20)	0.2	>10x[g]	
Carbon intensity of land-based passenger transport (gCO_2/pkm)	100 (2014)	35–60	0		Insufficient data	-3.5	Insufficient data	
Share of electric vehicles in light-duty vehicle sales (%)	8.7 (2021)[c]	75–95	100 (2035)		1.7 (2017–21)	8.5	5x	[e]
Share of electric vehicles in the light-duty vehicle fleet (%)	1.3 (2021)[c]	20–40	85–100		0.24 (2017–21)	3.2	>10x	
Share of battery electric vehicles and fuel cell electric vehicles in bus sales (%)	44 (2021)[c]	60	100		-0.1 (2017–21)	1.8	>10x[h]	[e]
Share of battery electric vehicles and fuel cell electric vehicles in medium- and heavy-duty vehicle sales (%)	0.2 (2021)[c]	30	99		Insufficient data	3.3	Insufficient data	[e]
Share of sustainable aviation fuels in global aviation fuel supply (%)	0.03 (2020)	13–18	78–100		Insufficient data	1.5	Insufficient data	[e]
Share of zero-emission fuels in maritime shipping fuel supply (%)	0 (2018)	5–17	84–93		Insufficient data	0.92	Insufficient data	[e]

TABLE A1 | Summary of Acceleration Factor Calculations (continued)

INDICATOR	MOST RECENT HISTORICAL DATA POINT (year)	2030 TARGET	2050 TARGET	TRAJECTORY OF CHANGE (Could this indicator experience some type of nonlinear change in the future?)	AVERAGE ANNUAL RATE OF HISTORICAL CHANGE (most recent 5 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]	EVALUATION (based on acceleration factors and, in some cases, expert judgment)
Forests and land[i]								
Deforestation (Mha/yr)	5.7 (2021)	1.9	0.31		-0.17 (2015–21)[j]	-0.43	2.5x	
Reforestation (total Mha)	130 (total gain, 2000–2020)	100	300		6.5 (2001–20)	10	1.5x[k]	
Peatland degradation (Mha/yr)	0.78 (annual average, 1990-2008)	0	0		Insufficient data	-0.035	Insufficient data	
Peatland restoration (total Mha)	No historical data	15	20		Insufficient data	1.5	Insufficient data	
Mangrove loss (ha/yr)	32,000 (annual average, 2017–2019)	4,900	N/A		850[l] (2010–19)	-2,400	N/A; U-turn needed	
Mangrove restoration (total Mha)	0.015 (total gain, 1999–2019)[m]	0.24	N/A		Insufficient data	0.024	Insufficient data	
Food and agriculture								
Agricultural production GHG emissions ($GtCO_2e$/yr)	5.8 (2019)	4.6	3.6		0.03 (2015–19)	-0.12	N/A; U-turn needed	
Crop yields (t/ha/yr)	6.6 (2020)	7.8	9.6		0.02 (2016–20)	0.12	6x	
Ruminant meat productivity (kg/ha/yr)	27 (2019)	33	42		0.44 (2015–19)	0.55	1.3x	
Share of food production lost (%)	14 (2016)	7	7		Insufficient data	-0.5	Insufficient data	
Food waste (kg/capita/yr)	121 (2019)	61	61		Insufficient data	-5.5	Insufficient data	
Ruminant meat consumption (kcal/capita/day)	91 (2019)	79	60		-0.25 (2015–19)	-1.1	5x	
Technological carbon removal								
Technological carbon removal ($MtCO_2$/yr)	0.54 (2020)	75	4,500		0.0097[n] (2017–20)	7.4	>10x	
Finance								
Global total climate finance (trillion US$/yr)	0.6 (2020)	5.2	5.1		0.039 (2016–20)	0.46	>10x	

TABLE A1 | Summary of Acceleration Factor Calculations (continued)

INDICATOR	MOST RECENT HISTORICAL DATA POINT (year)	2030 TARGET	2050 TARGET	TRAJECTORY OF CHANGE (Could this indicator experience some type of nonlinear change in the future?)	AVERAGE ANNUAL RATE OF HISTORICAL CHANGE (most recent 5 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]	EVALUATION (based on acceleration factors and, in some cases, expert judgment)
Finance (continued)								
Global public climate finance (trillion $/yr)	0.30 (2020)	1.31–2.61	1.29–2.57		0.015 (2016–20)	0.17	>10x	
Global private climate finance (trillion $/yr)	0.34 (2020)	2.61–3.92	2.57–3.86		0.023 (2016–20)	0.29	>10x	
Share of global emissions under mandatory corporate climate risk disclosure (%)	4 (2022)	75	75		0.8 (2018–22)	8.9	>10x	
Median carbon price in jurisdictions with pricing systems (2015$/$tCO_2e$)	23 (2022)	170–290	430–990		3.4 (2018–22)	26	8x	
Total public financing for fossil fuels (billion $/yr)	690 (2020)[o]	0	0		-15 (2016–20)	-69	5x	

Notes: %/yr = percent per year; 2015 US$/$tCO_2e$ = 2015 US dollars per tonnes of carbon dioxide equivalent; gCO2/kWh = grams of carbon dioxide per kilowatt-hour; gCO_2/pkm = grams of carbon dioxide per passenger kilometer; GHG = greenhouse gas; $GtCO_2e$/yr = gigatonnes of carbon dioxide equivalent per year; ha/yr = hectares per year; kcal/capita/day = kilocalories per capita per day; kg/capita/yr = kilograms per capita per year; kg/ha/yr = kilograms per hectare per year; $kgCO_2/m^2$ = kilograms of carbon dioxide per square meter; $kgCO_2$/t = kilograms of carbon dioxide per tonne; km/1,000 inhabitants = kilometers per 1,000 inhabitants; km/1M inhabitants = kilometers per 1 million inhabitants; Mha = million hectares; Mha/yr = million hectares per year; Mt = million tonnes; $MtCO_2$/yr = million tonnes of carbon dioxide per year; t/ha/yr = tonnes per hectare per year; US$/yr = US dollars per year.

[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. In previous reports, all acceleration factors under 10 were rounded to the 10th place (e.g., 7.4), which is 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.

[b] This data analysis is based on historical data collected before the IEA's recent most data update, and 2018 was the last available historical year at the time this analysis was conducted. The text might refer to newer historical data.

[c] Data for these indicators are not publicly available and were accessed with paid licenses to datasets or with permission from the data provider.

[d] Achieving below zero-carbon intensity implies biomass power generation with carbon capture and storage. Our targets limit bioenergy with carbon capture and storage use to 5 $GtCO_2$ per year in 2050. See Schumer et al. for further information about our sustainability criteria.

[e] The category of progress was adjusted for indicators categorized as exponential change likely, using methods outlined in Schumer et al. (2022), and so in these instances, the category of progress identified does not always match the acceleration factor calculated using a linear trendline.

[f] Energy intensity is the amount of energy used per square meter of floor area, including heating, cooling, and appliances. Publicly available data report only energy intensity trends for all buildings combined, not for residential and commercial buildings separately. In calculating acceleration factors, we use this combined energy intensity trend and assume that the historical rate of change is the same for both types of buildings.

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

[h] We adjusted this indicator's category of progress, using methods outlined in Schumer et al. (2022). Historically, the share of battery electric vehicles and fuel cell electric vehicles in bus sales globally has been highly dependent on the adoption of electric buses in China. But from 2018 to 2020, sales in China dipped, in part, due to changing subsidies and because the share of electric buses in many Chinese cities' fleets is fast approaching 100 percent (BNEF 2021b). From 2017 to 2021, the average annual rate of change in sales share was -0.1 percentage points, suggesting that recent rates of change are heading in the wrong direction entirely. However, the sales share picked back up from 2020 to 2021, surpassing their previous peak. And when accounting for the longer-term trend, it is clear that the change in this indicator is not going in the wrong direction. Therefore, we set the acceleration factor as >10x and categorize this indicator as off track.

[i] Indicators for forests and land experience high interannual variability in historical data due to both anthropogenic and natural causes. Accordingly, we use 10 years instead of 5 years to calculate the linear trendline where possible.

[j] For this indicator, we calculated a 7-year trendline using data from 2015 to 2021 due to temporal inconsistencies in the data before and after 2015 (Weisse and Potapov 2021).

[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) is used to estimate the historical rate of change, rather than a linear trendline.

[l] Historical data from Murray et al. (2022), which estimated mangrove loss for six three-year epochs. Gross loss was divided by the number of years in each epoch to determine the average annual loss rate, and a linear trendline was calculated using these data.

[m] Murray et al. (2022) estimated that 0.18 Mha of gross mangrove gain occurred from 1999 to 2019, only 8 percent of which can be attributed to direct human activities, such as mangrove restoration. Accordingly, this report does not use gross mangrove gain to approximate mangrove restoration. We estimate the most recent historical data point for mangrove restoration by taking 8% of the total gross mangrove gain from 1999-2019. See Schumer et al. (2022) for more information.

[n] Due to limited data, the linear trendline for this indicator was calculated using four years of data, rather than five years.

[o] Data on capital expenditure by G20 state-owned entities on fossil fuels was not available for 2020, so the 2019 figure of $250 billion is used.

Sources: 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 2021* and *State of Climate Action 2022*

The table below indicates if and why each indicator's acceleration factor and category of progress changed from the *State of Climate Action 2021* (Boehm et al. 2021) to the *State of Climate Action 2022*.

For most indicators, a combination of several factors, such as updates in methods, an additional year of data, or changes in underlying datasets, likely spurred these changes. And while it is difficult to disentangle these effects, we identify three key explanations:

1. Target change

For some indicators, the target itself has changed. This means that, in the *State of Climate Action 2022*, 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 Schumer et al. (2022).

2. Data change

A change in historical data between the 2021 and 2022 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 five-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 the table below, we indicate whether there was a change in the dataset or a new data point added for each indicator.

3. Methodology change

As described in Schumer et al. (2022), the method used to calculate the 5-year trendline (or 10-year trendline, used for indicators as described in Schumer et al. 2022) has been adopted for this year's report. As this trend is key to calculating the acceleration factor, the change in methodology has an impact on all indicators. Nevertheless, we only use "methodology change" as the main explanation in Table B1 if it is clear that it is the change in methodology (and not in target or data) that is mainly responsible for the change in acceleration factor. To assess whether this is the case, we calculated the acceleration factor that would result from this year's data using last year's methods, as well as the acceleration factor that would result from using last year's data with this year's method. If the values deviate significantly from those of both reports, we attribute the deviation to the change in methods. In addition to this methodology change, due to the high uncertainty associated with land-use data, separate methods were developed for some forests and land indicators following Boehm et al. (2021), which also impact the acceleration factors. This is also described in Schumer et al. (2022).

Finally, some indicators and targets have been established in this report that were not tracked in previous iterations of the report. These indicators are labeled as **new indicator**. For other indicators, in particular exponential change likely indicators without acceleration factors and indicators with insufficient data, no change between the reports is observed. These are labeled as **no difference**.

TABLE B1 | Changes in acceleration factors and categories of progress between *State of Climate Action 2021* and *State of Climate Action 2022*

2022 INDICATOR	BOEHM ET AL. 2021 ACCELERATION FACTOR	BOEHM ET AL. 2021 CATEGORY OF PROGRESS	BOEHM ET AL. 2022 ACCELERATION FACTOR	BOEHM ET AL. 2022 CATEGORY OF PROGRESS	EXPLANATION OF DIFFERENCES BETWEEN 2021 AND 2022
Power					
Carbon intensity of electricity generation (gCO_2/kWh)	3.2x	✕	5x	✕	Data change: An additional year of data
Share of zero-carbon sources in electricity generation (%)[a]	N/A; progress evaluated based on expert judgment and the literature	!	6x	!	No difference[b]

TABLE B1 | Changes in acceleration factors and categories of progress between *State of Climate Action 2021* and *State of Climate Action 2022* (continued)

2022 INDICATOR	BOEHM ET AL. 2021 ACCELERATION FACTOR	BOEHM ET AL. 2021 CATEGORY OF PROGRESS	BOEHM ET AL. 2022 ACCELERATION FACTOR	BOEHM ET AL. 2022 CATEGORY OF PROGRESS	EXPLANATION OF DIFFERENCES BETWEEN 2021 AND 2022
Power (continued)					
Share of unabated coal in electricity generation (%)	5.2x		6x		Data change: An additional year of data
Share of unabated fossil gas in electricity generation (%)	N/A	N/A	N/A; U-turn needed		New indicator
Buildings					
Energy intensity of building operations (% of 2015 levels)	2.7x (residential and commercial)		7x / 5x (residential / commercial)		Methodology change
Carbon intensity of building operations ($kgCO_2/m^2$)	Insufficient data		Insufficient data		No difference
Retrofitting rate of buildings (%/yr)	Insufficient data		Insufficient data		No difference
Industry					
Share of electricity in the industry sector's final energy demand (%)	1.1x		1.7x		Data change: An additional year of data
Carbon intensity of global cement production ($kgCO_2$/t cement)	N/A; step change needed.	Stagnant	>10x		Data change: New dataset used
Carbon intensity of global steel production ($kgCO_2$/t steel)	N/A; step change needed.	Stagnant	N/A; U-turn needed		Data change: An additional year of data
Green hydrogen production (Mt)	N/A; progress evaluated based on expert judgment and the literature		>10x		No difference[b]
Transport					
Share of kilometers traveled by passenger cars (%)	N/A; U-turn needed		N/A; U-turn needed		No difference
Number of kilometers of rapid transit (metro, light-rail and bus rapid transit) per 1 million inhabitants (in the top 50 emitting cities) (km/1M inhabitants)	N/A	N/A	6x		New indicator
Number of kilometers of high-quality bike lanes per 1,000 inhabitants (in the top 50 emitting cities) (km/1,000 inhabitants)	N/A	N/A	>10x		New indicator
Carbon intensity of land-based passenger transport (gCO_2/pkm)	Insufficient data		Insufficient data		No difference

TABLE B1 | Changes in acceleration factors and categories of progress between *State of Climate Action 2021* and *State of Climate Action 2022* (continued)

2022 INDICATOR	BOEHM ET AL. 2021 ACCELERATION FACTOR	BOEHM ET AL. 2021 CATEGORY OF PROGRESS	BOEHM ET AL. 2022 ACCELERATION FACTOR	BOEHM ET AL. 2022 CATEGORY OF PROGRESS	EXPLANATION OF DIFFERENCES BETWEEN 2021 AND 2022
Transport (continued)					
Share of electric vehicles in light-duty vehicle sales (%)	N/A; progress evaluated based on expert judgment and the literature	!	5x	!	No difference[b]
Share of electric vehicles in the light-duty vehicle fleet (%)	N/A; progress evaluated based on expert judgment and the literature	×	>10x	×	No difference[b]
Share of battery electric vehicles and fuel cell electric vehicles in bus sales (%)	N/A; progress evaluated based on expert judgment and the literature	!	>10x	!	No difference[b]
Share of battery electric vehicles and fuel cell electric vehicles in medium- and heavy-duty vehicle sales (%)	N/A; progress evaluated based on expert judgment and the literature	×	Insufficient data	×	No difference[b]
Share of sustainable aviation fuels in global aviation fuel supply (%)	N/A; progress evaluated based on expert judgment and the literature	×	Insufficient data	×	No difference[b]
Share of zero-emission fuels in maritime shipping fuel supply (%)	N/A; progress evaluated based on expert judgment and the literature	×	Insufficient data	×	No difference[b]
Forests and land					
Deforestation (Mha/yr)	N/A; U-turn needed	↩	2.5x	×	Methodology change
Reforestation (total Mha)	3.2x	×	1.5x	!	Target change
Peatland degradation (Mha/yr)	Insufficient data	?	Insufficient data	?	Target change
Peatland restoration (total Mha)	Insufficient data	?	Insufficient data	?	Target change
Mangrove loss (ha/yr)[c]	Insufficient data	?	N/A; U-turn needed	↩	Target change
Mangrove restoration (total Mha)[d]	2.7x	×	Insufficient data[e]	?	Target change
Food and agriculture					
Agricultural production GHG emissions ($GtCO_2e/yr$)	N/A; U-turn needed	↩	N/A; U-turn needed	↩	No difference
Crop yields (t/ha/yr)	1.9x	!	6x	×	Data change: An additional year of data
Ruminant meat productivity (kg/ha/yr)	1.6x	!	1.3x	!	Data change: An additional year of data
Share of food production lost (%)	Insufficient data	?	Insufficient data	?	No difference

TABLE B1 | Changes in acceleration factors and categories of progress between *State of Climate Action 2021* and *State of Climate Action 2022* (continued)

2022 INDICATOR	BOEHM ET AL. 2021 ACCELERATION FACTOR	BOEHM ET AL. 2021 CATEGORY OF PROGRESS	BOEHM ET AL. 2022 ACCELERATION FACTOR	BOEHM ET AL. 2022 CATEGORY OF PROGRESS	EXPLANATION OF DIFFERENCES BETWEEN 2021 AND 2022
Food and agriculture (continued)					
Food waste (kg/capita/yr)	Insufficient data	?	Insufficient data	?	No difference
Ruminant meat consumption (kcal/capita/day)	1.5x	!	5x	✕	Data change: An additional year of data
Technological carbon removal					
Technological carbon removal ($MtCO_2$/yr)	N/A; progress evaluated based on expert judgment and the literature	✕	>10x	✕	Methodology change
Finance					
Global total climate finance (trillion US$/yr)	13x[f]	✕	>10x	✕	Target change
Global public climate finance (trillion $/yr)	5x	✕	>10x	✕	Target change
Global private climate finance (trillion $/yr)	23x[f]	✕	>10x	✕	Target change
Share of global emissions under mandatory corporate climate risk disclosure (%)[g]	Insufficient data	?	>10x	✕	Target change
Median carbon price in jurisdictions with pricing systems (2015$/t CO_2e)[h]	N/A; step change needed.	Stagnant	8x	✕	Target change
Total public financing for fossil fuels (billion $/yr)	1.1x	!	5x	✕	Methodology change

Notes: 2015 US$/t$CO_2$e = 2015 US dollars per tonnes of carbon dioxide equivalent; gCO_2/kWh = grams of carbon dioxide per kilowatt-hour; gCO_2/pkm = grams of carbon dioxide per passenger kilometer; GHG = greenhouse gas; GtCO_2e/yr = gigatonnes of carbon dioxide equivalent per year; ha/yr = hectares per year; kcal/capita/day = kilocalories per capita per day; kg/capita/yr = kilograms per capita per year; kg/ha/yr = kilograms per hectar per year; kgCO_2/m^2 = kilograms of carbon dioxide per square meters; kgCO_2/t = kilograms of carbon dioxide per tonne; km/1,000 inhabitants = kilometers per 1,000 inhabitants; km/1M inhabitants = kilometers per 1 million inhabitants; Mha = million hectares; Mha/yr = million hectares per year; Mt = million tonnes; MtCO_2/yr = million tonnes of carbon dioxide per year; t/ha/yr = tonnes per hectar per year.

[a] This indicator changed slightly from Boehm et al. (2021), where it was presented as share of renewables in electricity generation. See Appendix A in Schumer et al. (2022).

[b] In Boehm et al. (2021), acceleration factors for indicators with a trajectory of exponential change likely were not calculated. For this indicator this has no implications for the category of progress, hence it is categorized as no difference,

[c] This indicator changed slightly from Boehm et al. (2021), where it was presented as coastal wetlands conversion rate. See Appendix A in Schumer et al. (2022).

[d] This indicator changed slightly from Boehm et al. (2021), where it was presented as coastal wetlands restoration. See Appendix A in Schumer et al. (2022).

[e] Boehm et al. (2021) used gross gains in mangrove extent globally as a proxy for mangrove restoration. However, a study (Murray et al. 2022) published since Boehm et al. (2021) finds that only 8 percent of these gains are attributable to direct human activities. We therefore deem these data to no longer serve as a good proxy for mangrove restoration and categorize the indicator as data insufficient.

[f] In this year's report, we note acceleration factors higher than 10 as >10x. In previous reports, all acceleration factors under 10 were rounded to the 10th place (e.g., 7.4), which is 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.

[g] This indicator changed slightly from Boehm et al. (2021), where it was presented as corporate climate risk disclosure. See Appendix A in Schumer et al. (2022).

[h] This indicator changed slightly from Boehm et al. (2021), where it was presented as share of global emissions covered by a carbon price of at least $135/tCO2e. See Appendix A in Schumer et al. (2022).

Sources: Boehm et al. (2021) and authors' analysis based on data sources listed in each section.

ABBREVIATIONS

AFOLU	agriculture, forestry, and other land uses
BECCS	bioenergy with carbon capture and storage
BEV	battery electric vehicle
CCUS	carbon capture, utilization, or storage
CGIAR	formerly the Consultative Group on International Agricultural Research
COP26	26th Session of the Conference of the Parties
CO_2	carbon dioxide
CO_2e	carbon dioxide equivalent
CPI	Climate Policy Initiative
DAC	direct air capture
DFI	development finance institution
DRI	direct reduced iron
EAF	electric arc furnace
ETS	emissions trading system
EV	electric vehicle
FCEV	fuel cell electric vehicle
gCO_2	grams of carbon dioxide
GDP	gross domestic product
GFANZ	Glasgow Financial Alliance for Net Zero
GHG	greenhouse gas
Gt	gigatonne
GW	gigawatt
ha	hectare
ICE	internal combustion engine
IMO	International Maritime Organization
IPCC	Intergovernmental Panel on Climate Change
kcal	kilocalorie
kWh	kilowatt-hour
LDV	light-duty vehicle
MDB	multilateral development bank
Mha	million hectares
MHDV	medium- and heavy-duty vehicle
Mt	million tonnes
OECD	Organisation for Economic Co-operation and Development
pkm	passenger kilometer
PV	photovoltaics
RD&D	research, development, and demonstration
REDD+	reducing emissions from deforestation and forest degradation
SAF	sustainable aviation fuel
SDGs	Sustainable Development Goals
SME	small-to-medium enterprise
TCFD	Task Force on Climate-Related Financial Disclosures
TWh	terawatt-hour
UNFCCC	UN Framework Convention on Climate Change
VRE	variable renewable energy
ZEF	zero-emission fuel
ZEV	zero-emission vehicle

ENDNOTES

1. Note that, while the IPCC treats AFOLU as one system, this report splits AFOLU into two sections: forests and land, as well as food and agriculture, given the number of indicators in each section.
2. Identifying critical shifts for each system, 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 innumerable 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 system than to the transport system or vice versa) can be pursued to hold 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 systemwide transformations that must occur is relatively limited, and the IPCC makes clear that, together, all systems will eventually have to dramatically lower emissions to limit global warming to 1.5°C (IPCC 2022b). So, if a transformation across one system is slower than this global requirement, another needs to transition proportionately faster, or additional CO_2 must be removed from the atmosphere. Arguing that a system 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 systemwide transformations needed to limit global temperature rise to 1.5°C into a set of critical shifts is asking whether a system can decarbonize by 2050. If so, how and how quickly, and if not, why (Climate Action Tracker 2020b)?
3. A comprehensive assessment of equity and biodiversity is beyond the scope of the *State of Climate Action* series. See "Section 7: Key Limitations" of Schumer et al. (2022) for more information.
4. Note that we use the term "exponential" instead of "S-curve" for communication purposes, because it is a more commonly known term. Not all stages of an S-curve are exponential.
5. While the other Forests and Land indicators used a ten-year trendline, for our deforestation indicator, we calculated a 7-year trendline, using data from 2015 to 2021 due to temporal inconsistencies in the data before and after 2015 (Weisse and Potapov 2021).
6. This is an important methodological update from last year's report, where we calculated the linear trend by drawing a straight line between the most recent data point and the data point from five years prior, therefore using just two moments in time. We made the change because a line of best fit better reflects trends, as it is less impacted by small fluctuations, uncertainties in the data, and outliers, such as outliers in 2020 values due to the COVID-19 pandemic. Using a line of best fit ensures that the current value and the value from five years ago influence the linear trend but do not exclusively determine it. However, in some instances, due to data limitations, we revert back to the methods for assessing progress from Boehm et al. (2021). This deviation from our standard methods is noted accordingly.
7. Note that for the indicators with targets presented as a range, we assess progress based on the midpoint of that range—that is, we compare the historical rates of change to the rates of change required to reach the midpoint.
8. 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 for acceleration factors higher than 10, we note as >10. In previous reports, all acceleration factors under 10 were rounded to the 10th place (e.g., 7.4), which is 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.
9. In a change from the *State of Climate Action 2021*, 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.
10. Defined as generation by solar, wind, hydropower, nuclear, geothermal, marine, and biomass technologies, all of which generate negligible CO_2 during their operational cycle.
11. Otherwise known as natural gas.
12. Defined as the consumption of fossil fuels without measures to abate carbon dioxide emissions. Abatement techniques include technologies such as carbon capture, utilization, or storage (CCUS).
13. In the *State of Climate Action 2022*, we have amended the "Share of renewables in electricity generation" indicator from the 2021 report to this year include nuclear power and therefore changed the name to "Share of zero-carbon sources in electricity generation." The intent is for this indicator to reflect the broad range of literature on power system transition. This change has considerably raised the 2030 benchmark range from last year's narrower indicator.
14. Specifically, Germany, France, Austria, Netherlands, and the United Kingdom.
15. This target is based on the Climate Action Tracker work on sectoral benchmarks that are compatible with the Paris Agreement (Climate Action Tracker 2020b), which includes carbon intensity 2030 benchmarks for the United States, the European Union, Brazil, India, China, and South Africa. Because these countries and European regional bloc cover a large share of global emissions and population, this report uses these national and regional benchmarks to establish global target ranges for 2030 and 2050. More specifically, the targets in this report are specified as a range that encompasses all benchmarks for the countries and regional bloc from Climate Action Tracker (2020b).

16. A heat pump transfers heat energy from the air or ground to a building's heating system. A heat pump works in a similar manner to a refrigerator or an air conditioner in that it puts a refrigerant through pressure cycles to transfer heat. Heat pumps are highly efficient—more heat energy is transferred than energy required to power the heat pump—and are electric, allowing them to be fully decarbonized.

17. "District heating" refers to infrastructure that distributes heat through a neighborhood or city, usually via water running through insulated pumps. A centralized heat source, such as a power plant, underground heat, or waste heat from industry, provides energy to the network. Heat exchangers are used to extract heat from the network for space or water heating in individual buildings.

18. Direct emissions include emissions generated from sources that are owned or controlled by the industrial operator, while indirect emissions refer to emissions that are the result of the activities of the industrial operator but are generated at sources owned or controlled by another institution (Greenhouse Gas Protocol n.d.). Direct emissions include energy-related emissions caused by the combustion of fuels, and process emission caused by chemical reactions. Indirect emissions typically include emissions from electricity and purchased heat.

19. Other major-emitting industries include aluminum, chemicals, and pulp and paper (Vass et al. 2021). We exclude them due to data limitations. However, additional industries may be added in future reports.

20. Clinker, which acts as the "glue" or binding component in cement, is responsible for the majority (90 percent) of cement emissions as it both requires high heat and generates process emissions.

21. We no longer include the "stagnant" category of global progress featured in Boehm et al. (2021). Instead, we now categorize recent progress for this indicator as well off track.

22. "Electrolysis" refers to the process of using electricity to split water into hydrogen and oxygen, and this reaction occurs in an electrolyzer.

23. Recent research shows that the mitigation potential of hydrogen could be overestimated considering that hydrogen is an indirect greenhouse gas and could be released into the atmosphere through leakage, venting, and purging (Ocko and Hamburg 2022).

24. Author's assessment of data from the Global Coal Plant Tracker. Plants including blast furnace technology are included.

25. A pilot plant has recently been funded to produce ordinary cement using basalt, instead of limestone, which doesn't produce CO_2 process emissions (Clifford 2022; Shapiro 2019).

26. In some cases, particularly in industries where green hydrogen will be needed, it might be cheaper to abandon a plant and build a new one near richer sources of renewables than to expand energy infrastructure.

27. Several existing initiatives have a carbon price of less than US$10/t$CO_2$, which is not nearly enough to drive change in the hard-to-decarbonize industrial sectors. Energy Transitions Commission analysis, for example, recommends introducing a $100/t$CO_2$ price on cement (ETC 2021).

28. Notable exceptions include the cement sector, where Asia is leading in energy efficiency with a younger technology stock.

29. Rough estimates based on Deign (2021). The actual required capacity will depend on factors such as the efficiency of electrolyzers and capacity factors of the renewable energy power generation.

30. The dataset used for this indicator, the IEA Energy Technology Perspectives 2017, is the last available dataset.

31. Includes urban transit buses and excludes intercity buses and minibuses.

32. Battery electric options are also in development for short-distance maritime shipping and travel (Kersey et al. 2022) but are not included in this indicator. Biofuels such as biomethanol may provide some CO_2 reductions compared to traditional heavy fuel oil or marine diesel oil, but do not meet the definition of zero-emission fuels.

33. 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 book-keeping models. This estimate is currently about 5.5 GtCO_2 per year higher than aggregate global estimates of net anthropogenic CO_2 emissions from National Greenhouse Gas Inventories. While no method is inherently preferable over another, this section follows the "Summary for Policymakers" in IPCC (2022b), as well as UNEP (2021c), in reporting the estimate from global book-keeping models. Note that this estimate of net anthropogenic CO_2 emissions from global book-keeping models is complemented by data on peatland drainage and fires (IPCC 2022b).

34. The IPCC (2022b) reports the mean of three book-keeping models, as presented in the *Global Carbon Budget 2020*. Published after Working Group III's Contribution to AR6, the *Global Carbon Budget 2021* features updates in the datasets underpinning the study's three book-keeping models, which now show a decreasing trend in net CO_2 emissions from land use, land-use change, and forestry since 2000 (Friedlingstein et al. 2022). However, Friedlingstein et al. (2022) caution that these new data do not include global emissions from forest degradation and may not adequately capture CO_2 released from recent increases in deforestation across Brazil, specifically.

35. "Land-based mitigation measures" or "land-based measures" in Section 6 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.

36. The IPCC (2022a) found that land-based mitigation measures from forests and other ecosystems that cost up to $100 per tCO_2e can deliver between 4.2 and 7.3 $GtCO_2e$ per year from 2020 to 2050, with the bottom range representing the median estimate from integrated assessment models and the top range representing the median estimate from sectoral studies (IPCC 2022b).

37. Following Roe et al. (2021), this report narrows Boehm et al. (2021)'s targets and indicator for coastal wetlands, which included mangrove forests, seagrass meadows, and salt marshes, to focus solely on mangrove forests.

38. Although FAO collects and publishes national-level statistics on the area of managed forests every five years, there are currently no global datasets that comprehensively and consistently map managed forests. Similarly, no such datasets exist for grasslands. Due to these data limitations, this report does not include targets for two "sustainably manage" wedges in Roe et al. (2021): improved forest management and grassland fire management.

39. Due to updates to the dataset on drivers of deforestation (Curtis et al. 2018), as well as changes in the methodology used to estimate deforestation in this report, this estimate differs slightly from prior *State of Climate Action* reports. Annual estimates over the 2001 to 2020 time period following the update to Curtis et al. (2018) differ by an average of 3 percent.

40. We have changed our methods for categorizing progress made toward near-term targets since Boehm et al. (2021); see Schumer et al. (2022) for more information. These methodological changes, rather than an additional year of data, are responsible for the upgrade in this indicator's category of progress from heading in the wrong direction in Boehm et al. (2021) to well off track in this report. More specifically, if we employ methods from Boehm et al. (2021) with the updated data from 2015 to 2021, we would still categorize this indicator as heading in the wrong direction.

41. 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 Schumer et al. (2022) for more information on how these targets were established.

42. Tree cover gain is defined as woody vegetation that grew from a height of less than 5 m in 2000 to a height of greater than or equal to 5 m in 2020, or woody vegetation that had a height increase by greater than or equal to 100 percent from 2000 to 2020 (Potapov et al. 2022a). See Schumer et al. (2022) for more information.

43. This target has changed between Boehm et al. (2021) and this year's report. See Schumer et al. (2022) for more information.

44. 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; Roe et al. 2021). Relatedly, this report also 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 hold 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, are subject to saltwater intrusion, or have already been 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 Griscom et al. 2017 notes, 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. 2019b; Roe et al. 2019). We followed these studies and set a more ambitious target than Roe et al. (2021), which involves restoring nearly half of degraded peatlands (recently estimated at 46 Mha by Humpenöder et al. 2020) by midcentury. This target, then, represents an important starting point rather than a definitive goal for policymakers.

45. 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 critical gap in the scientific community's understanding of the role that mangrove forests play in climate change mitigation (Macreadie et al. 2019).

46. 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 1 m is included, and the estimated carbon density of these ecosystems is 502 tonnes of carbon per hectare (Goldstein et al. 2020). When accounting for carbon stored at greater depths (i.e., down to 1 m for forests and 2 m for mangroves), mangrove carbon density is roughly four to six times higher than that of terrestrial forests (Temmink et al. 2022).

47. Murray et al. (2022) report a 95 percent confidence interval of 0.33 to 0.68 Mha for this estimate.

48. Estimates of gross mangrove loss vary. For example, Goldberg et al. (2020) find that rates of mangrove loss have been declining from 2000 to 2016. Differences in estimates can be due to several factors, including lack of alignment in the time period assessed across studies and differences in methodology used for mapping.

49. This target and associated indicator are from Roe et al. (2021), who derive their estimates from Griscom et al. (2020), who focus solely on mitigation outcomes attributed to human activities. It does not include 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 annual carbon sequestration rate associated with this target for mangrove restoration is likely an overestimate, given that it does not account for methane fluxes that occur naturally within these ecosystems and partially offset their carbon sequestration rates (Rosentreter et al. 2018, 2021).

50. Murray et al. (2022) report a 95 percent confidence interval of 0.09 to 0.30 Mha for this estimate.

51. Note that Roe et al. (2019) exclude the biophysical effects of deforestation demonstrated by Lawrence et al. (2022) from their estimate of mitigation potential for avoided emissions from reducing deforestation.

52. Note that this estimate of cost-effective mitigation potential accounts for the restoration of 15 Mha of degraded peatlands from 2020 to 2030, but it excludes the mitigation potential associated with the restoration of another 5 Mha of degraded peatlands from 2030 to 2050, as the model in Humpenöder et al. (2020) indicates that achieving this additional restoration would require a higher carbon price.

53. CO_2 fertilization, defined as the increase in plant photosynthesis and water-use efficiency in response to increased atmospheric concentrations of CO_2, is primarily responsible for this recent historical increase in the global land sink (IPCC 2021).

54. Findings from the literature on the effectiveness of 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.

55. "Governance" refers to "the traditions and institutions by which authority in a country is exercised," including "the process by which governments are selected, monitored and replaced; the capacity of the government to effectively formulate and implement sound policies; and the respect of citizens and the state for the institutions that govern economic and social interactions among them" (Kaufmann and Kraay 2007).

56. The World Bank's "rule of law" indicator captures perceptions of the extent to which agents have confidence in and abide by the rules of society, and in particular the quality of contract enforcement, property rights, the police, and the courts, as well as the likelihood of crime and violence (Kaufmann and Kraay 2020).

57. The World Bank's "government effectiveness" indicator captures perceptions of the quality of public services, the quality of the civil service and the degree of its independence from political pressures, the quality of policy formulation and implementation, and the credibility of the government's commitment to such policies (Kaufmann and Kraay 2020).

58. The World Bank's "control of corruption" indicator captures perceptions of the extent to which public power is exercised for private gain, including both petty and grand forms of corruption, as well as the capture of the state by elites and private interests (Kaufmann and Kraay 2020).

59. Following Seymour and Busch (2016), we recognize that many use REDD+ as shorthand for initiatives or finance dedicated to reducing emissions from deforestation and degradation, but we define the term more narrowly as the framework negotiated under the UNFCCC and associated activities.

60. Most climate finance stays within countries, including over 90 percent of private climate flows (IPCC 2022b). This places developing countries across sub-Saharan Africa, the Middle East and North Africa, South Asia, and Latin America at a significant disadvantage, given that the United States, Canada, Western Europe, and East Asia and the Pacific accounted for an average of more than 75 percent of global climate finance flows in 2019 and 2020 (Buchner et al. 2021).

61. Searchinger et al. (2020) find that OECD and developing economies accounting for two-thirds of agricultural production provided an average of $600 billion per year in agricultural support from 2014 to 2016. This estimate includes support through direct spending, special tax benefits, and market barriers that increase prices to consumers.

62. This section uses FAOSTAT (2022) as its data source of agricultural production emissions, because these data are more detailed for this sector than those of the International Center for Tropical Agriculture (CAIT). 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.

63. To best approximate direct emissions from farms and pastures (and to avoid double counting with Section 6) we use FAOSTAT emissions categories that IPCC used for agriculture, but we removed drained organic soils (or peatlands), which are covered in Section 6 (FAO 2021; see also Tubiello et al. 2021).

64. 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.

65. FAOSTAT's definition of Oceania includes Australia, New Zealand, Melanesia, Micronesia, and Polynesia.

66. In this section, consumption data are given in availability, which is defined in FAO's Food Balance Sheets (FAOSTAT 2022) as the per capita amount of ruminant meat available at the retail level and is a proxy for consumption.

67. To establish these targets, the pathways in the IPCC Special Report on 1.5°C are filtered for sustainability criteria outlined in Fuss et al. (2018), and the median values are used for the amount of technological carbon removal in 2030 and 2050.

68. Progress is estimated based on publicly available data, but better data availability would enable more transparency in tracking progress.

69. The indicator is classified as "exponential change possible" because while it tracks a bundle of new technologies, each of which may follow an S-curve, it is also a public good that requires policy support. Natural market forces that can propel growth in technologies like solar and electric vehicles may not apply to carbon removal technologies.

70. 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).

71. A number of gaps exist in the climate finance tracking data, and 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).

72. 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 (Buchner et al. 2021), so total public climate finance may be higher than is currently tracked.

73. Total climate finance from developed to developing countries, including export credits and mobilized private finance, was $83.3 billion in 2020 (OECD 2022a).

74. 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.

75. Disclosure requirements are not uniform between countries and apply to different or select types of firms (e.g., financial institutions or publicly traded firms). 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.

76. 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).

77. 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 2021).

78. Countries in the G20, the OECD, and 33 other major energy producing and consuming economies.

79. While fossil fuel companies have claimed to support carbon pricing in some circumstances, privately industry lobbyists have admitted this was a public relations ploy to appear supportive of climate action, because they knew pricing would not happen (McGreal 2021). In addition, fossil fuel industry proposals for carbon pricing mechanisms have included poison pill elements such as providing them with immunity from legal liability for climate change (Irfan 2018).

REFERENCES

Abdalla, A.M., S. Hossain, O.B. Nisfindy, A.T. Azad, M. Dawood, and A.K. Azad. 2018. "Hydrogen Production, Storage, Transportation and Key Challenges with Applications: A Review." *Energy Conversion and Management* 165 (June): 602–27. doi:10.1016/j.enconman.2018.03.088.

Abnett, K. 2022. "EU Lawmakers Back Ban on New Fossil-Fuel Cars from 2035." Reuters, June 8. https://www.reuters.com/business/autos-transportation/eu-lawmakers-support-effective-ban-new-fossil-fuel-cars-2035-2022-06-08/.

Abramczyk, M., A.B. Jaffee, A. Chitkara, M. Diawara, A. Lerch, and J. Newcomb. 2017. "Positive Disruption: Limiting Global Temperature Rise to Well Below 2 C°." Basalt, CO: Rocky Mountain Institute. https://rmi.org/insight/positive_disruption_limiting_global_temperature_rise/.

Abramson, E., D. McFarlane, and J. Brown. 2020. "Transport Infrastructure for Carbon Capture and Storage." Great Plains Institute and Regional Carbon Capture Deployment Initiative, June. https://www.betterenergy.org/wp-content/uploads/2020/06/GPI_RegionalCO2Whitepaper.pdf.

Adams, M., V. Burrows, and D. Czerwinska. 2020. "Asia Pacific Embodied Carbon Primer." London: World Green Building Council. https://www.worldgbc.org/sites/default/files/Asia%20Pacific%20Embodied%20Carbon%20Primer_FINAL_v5_240920_1.pdf.

ADB (Asian Development Bank). 2021. "ADB Energy Policy and Program, 2009–2019." Manilla: ADB. https://www.adb.org/documents/sector-wide-evaluation-adb-2009-energy-policy-and-program-2009-2018.

Adriazola-Steil, C., H. Ohlund, S. El-Samra, F. Targa, and G. Zayas. 2021. "Investing for Momentum in Active Mobility." Transport Decarbonization Investment Series. Washington, DC: World Bank. http://hdl.handle.net/10986/36617.

AEMO (Australian Energy Market Operator). 2021a. "Draft 2022 Integrated System Plan." December. Melbourne: AEMO. https://aemo.com.au/-/media/files/major-publications/isp/2022/draft-2022-integrated-system-plan.pdf.

AEMO. 2021b. "NEM Data Dashboard." December. Melbourne: AEMO. https://aemo.com.au/en/energy-systems/electricity/national-electricity-market-nem/data-nem/data-dashboard-nem.

Ahmed, N., A. Marriott, N. Dabi, M. Lowthers, M. Lawson, and L. Mugehera. 2022. "Inequality Kills." Oxford, UK: Oxfam. https://www.oxfam.org/en/research/inequality-kills.

AIM for Climate. 2022. "AIM for Climate Seeks to Double Investment in Climate-Smart Agriculture and Food Systems Innovation by COP27." https://www.moccae.gov.ae/en/media-center/news/21/2/2022/aim-for-climate-seeks-to-double-investment-in-climate-smart-agriculture-and-food-systems-innovation-by-cop27.aspx#page=1.

Airbus. 2022. "The ZEROe Demonstrator Has Arrived." February 22. https://www.airbus.com/en/newsroom/stories/2022-02-the-zeroe-demonstrator-has-arrived.

Air Transport Action Group. 2021. "Waypoint 2050." Geneva: Air Transport Action Group. https://aviationbenefits.org/media/167417/w2050_v2021_27sept_full.pdf.

Alam, M., P.X.W. Zou, R.A. Stewart, E. Bertone, O. Sahin, C. Buntine, and C. Marshall. 2019. "Government Championed Strategies to Overcome the Barriers to Public Building Energy Efficiency Retrofit Projects." *Sustainable Cities and Society* 44 (January): 56–69. doi:10.1016/j.scs.2018.09.022.

Allen, C., A. Chuney, C. Holness, R. Jacobson, U. Kosar, and V. Suarez. 2022. "Setting DAC on Track: Strategies for Hub Implementation." Washington, DC: Carbon 180. https://static1.squarespace.com/static/5b9362d89d5abb8c51d474f8/t/6261d1890b76863f1047a2dd/1650577901659/Carbon180-SettingDACOnTrack.pdf.

Alova, G., P.A. Trotter, and A. Money. 2021. "A Machine-Learning Approach to Predicting Africa's Electricity Mix Based on Planned Power Plants and Their Chances of Success." *Nature Energy* 6 (2): 158–66. doi:10.1038/s41560-020-00755-9.

Alves-Pinto, H.N., P. Newton, and L.F.G. Pinto. 2015. "Reducing Deforestation and Enhancing Sustainability in Commodity Supply Chains: Interactions between Governance Interventions and Cattle Certification in Brazil." *Tropical Conservation Science* 8 (4): 1053–79. doi:10.1177/194008291500800414.

Amador, G., E. Burns, M. Glicksman, C. Holness, R.P. Jacobson, U. Kosar, C. Neidl, et al. 2021. "Zero, Then Negative: The Congressional Blueprint for Scaling Carbon Removal." Carbon180, May 13. https://www.ourenergypolicy.org/resources/zero-then-negative-the-congressional-blueprint-for-scaling-carbon-removal/.

Anchondo, C. 2022. "'First of Its Kind' CCS Project Opens in N.D." *E&E News*, July 19. https://subscriber.politicopro.com/article/eenews/2022/07/19/north-dakota-carbon-capture-project-kicks-off-00046355.

Andersen, R., C. Farrell, M. Graf, F. Muller, E. Calvar, P. Frankard, S. Caporn, and P. Anderson. 2017. "An Overview of the Progress and Challenges of Peatland Restoration in Western Europe: Peatland Restoration in Western Europe." *Restoration Ecology* 25 (2): 271–82. doi:10.1111/rec.12415.

Andrijevic, M., C.-F. Schleussner, M.J. Gidden, D.L. McCollum, and J. Rogelj. 2020. "COVID-19 40Recovery Funds Dwarf Clean Energy Investment Needs." *Science* 370 (6514): 298–300. doi:10.1126/science.abc9697.

Ansar, A., B. Caldecott, and J. Tilbury. 2013. "Stranded Assets and the Fossil Fuel Divestment Campaign: What Does Divestment Mean for the Valuation of Fossil Fuel Assets?" Oxford, UK: Smith School of Enterprise and the Environment, University of Oxford. https://www.smithschool.ox.ac.uk/publications/reports/SAP-divestment-report-final.pdf.

Argus Media. 2022. “EV Sales Rise in Latin America amid High Fuel Prices.” *Argus* (blog), July 20. https://www.argusmedia.com/en/news/2352765-ev-sales-rise-in-latin-america-amid-high-fuel-prices.

Arifanti, V.B. 2020. “Mangrove Management and Climate Change: A Review in Indonesia.” *IOP Conference Series: Earth and Environmental Science* 487 (1): 012022. doi:10.1088/1755-1315/487/1/012022.

Arthur, W.B. 1989. “Competing Technologies, Increasing Returns, and Lock-In by Historical Events.” *Economic Journal* 99 (394): 116. doi:10.2307/2234208.

Assunção, J., C. Gandour, and R. Rocha. 2013. “Does Credit Affect Deforestation? Evidence from a Rural Credit Policy in the Brazilian Amazon.” Rio de Janeiro: Climate Policy Initiative. https://climatepolicyinitiative.org/wp-content/uploads/2013/01/Does-Credit-Affect-Deforestation-Evidence-from-a-Rural-Credit-Policy-in-the-Brazilian-Amazon-Technical-Paper-English.pdf.

Australian Energy Regulator. 2022. “Annual Volume Weighted Average 30-Minute Prices—Regions.” https://www.aer.gov.au/wholesale-markets/wholesale-statistics/annual-volume-weighted-average-30-minute-prices-regions.

Azevedo-Ramos, C., and P. Moutinho. 2018. “No Man’s Land in the Brazilian Amazon: Could Undesignated Public Forests Slow Amazon Deforestation?” *Land Use Policy* 73 (April): 125–27. doi:10.1016/j.landusepol.2018.01.005.

Azevedo-Ramos, C., P. Moutinho, V.L. da S. Arruda, M.C.C. Stabile, A. Alencar, I. Castro, and J.P. Ribeiro. 2020. “Lawless Land in No Man’s Land: The Undesignated Public Forests in the Brazilian Amazon.” *Land Use Policy* 99 (December): 104863. doi:10.1016/j.landusepol.2020.104863.

Bang, G., and B. Lahn. 2020. “From Oil as Welfare to Oil as Risk? Norwegian Petroleum Resource Governance and Climate Policy.” *Climate Policy* 20 (8): 997–1009. doi:10.1080/14693062.2019.1692774.

Baragwanath, K., and E. Bayi. 2020. “Collective Property Rights Reduce Deforestation in the Brazilian Amazon.” *Proceedings of the National Academy of Sciences* 117 (34): 20495–502. doi:10.1073/pnas.1917874117.

Baranzini, A., and S. Carattini. 2017. “Effectiveness, Earmarking and Labeling: Testing the Acceptability of Carbon Taxes with Survey Data.” *Environmental Economics and Policy Studies* 19 (1): 197–227. doi:10.1007/s10018-016-0144-7.

Barrow, E., J. Kamugisha-Ruhombe, I. Nhantumbo, R. Oyono, and M. Savadogo. 2016. “Who Owns Africa’s Forests? Exploring the Impacts of Forest Tenure Reform on Forest Ecosystems and Livelihoods.” *Forests, Trees and Livelihoods* 25 (2): 132–56. doi:10.1080/14728028.2016.1159999.

Basma, H., A. Saboori, and F. Rodriguez. 2021. “Total Cost of Ownership for Tractor-Trailers in Europe: Battery Electric versus Diesel.” Washington, DC: International Council on Clean Transportation. https://theicct.org/sites/default/files/publications/TCO-BETs-Europe-white-paper-v4-nov21.pdf.

Basma, H., F. Rodríguez, J. Hildermeier, and A. Jahn. 2022. “Electrifying Last-Mile Delivery: A Total Cost of Ownership Comparison of Battery-Electric and Diesel Trucks in Europe.” Washington, DC: International Council on Clean Transportation and Regulatory Assistance Project. https://theicct.org/publication/tco-battery-diesel-delivery-trucks-jun2022/.

Basseches, J.A., R. Bromley-Trujillo, M.T. Boykoff, T. Culhane, G. Hall, N. Healy, D.J. Hess, et al. 2022. “Climate Policy Conflict in the U.S. States: A Critical Review and Way Forward.” *Climatic Change* 170 (3–4): 32. doi:10.1007/s10584-022-03319-w.

Bastos Lima, M.G., I.J. Visseren-Hamakers, J. Braña-Varela, and A. Gupta. 2017. “A Reality Check on the Landscape Approach to REDD+: Lessons from Latin America.” *Forest Policy and Economics* 78 (May): 10–20. doi:10.1016/j.forpol.2016.12.013.

Bataille, C. 2019. “Low and Zero Emissions in the Steel and Cement Industries—Barriers, Technologies and Policies.” Paris: Organisation for Economic Co-operation and Development. https://www.oecd.org/greengrowth/GGSD2019_IssuePaper_CementSteel.pdf.

Batres, M., F.M. Wang, H. Buck, R. Kapila, U. Kosar, R. Licker, D. Nagabhushan, et al. 2021. “Environmental and Climate Justice and Technological Carbon Removal.” *Electricity Journal* 34 (7): 107002. doi:10.1016/j.tej.2021.107002.

Bauer, G., C.-W. Hsu, and N. Lutsey. 2021. “When Might Lower-Income Drivers Benefit from Electric Vehicles? Quantifying the Economic Equity Implications of Electric Vehicle Adoption.” Washington, DC: International Council on Clean Transportation. https://theicct.org/publication/when-might-lower-income-drivers-benefit-from-electric-vehicles-quantifying-the-economic-equity-implications-of-electric-vehicle-adoption/.

BBC News. 2021. “Wales Transport: Freeze on All New Road Building Projects.” June 22. https://www.bbc.com/news/uk-wales-politics-57552390.

Bergek, A., S. Jacobsson, B. Carlsson, S. Lindmark, and A. Rickne. 2008. “Analyzing the Functional Dynamics of Technological Innovation Systems: A Scheme of Analysis.” *Research Policy* 37 (3): 407–29. doi:10.1016/j.respol.2007.12.003.

Bernhard, A. 2020. “The Great Bicycle Boom of 2020.” BBC. https://www.bbc.com/future/bespoke/made-on-earth/the-great-bicycle-boom-of-2020.html.

Bertoldi, P., and R. Mosconi. 2020. “Do Energy Efficiency Policies Save Energy? A New Approach Based on Energy Policy Indicators (in the EU Member States).” *Energy Policy* 139 (April): 111320. doi:10.1016/j.enpol.2020.111320.

Bertoldi, P., M. Economidou, V. Palermo, B. Boza-Kiss, and V. Todeschi. 2021. “How to Finance Energy Renovation of Residential Buildings: Review of Current and Emerging Financing Instruments in the EU.” *Wiley Interdisciplinary Reviews: Energy and Environment* 10 (1). doi:10.1002/wene.384.

BHHRC (Business and Human Rights Resource Centre). 2020. “Renewable Energy & Human Rights Benchmark.” June 29. https://www.business-humanrights.org/en/from-us/briefings/renewable-energy-human-rights-benchmark/.

Bieker, G. 2021. "A Global Comparison of the Life-Cycle Greenhouse Gas Emissions of Combustion Engine and Electric Passenger Cars." Berlin: International Council on Clean Transportation. https://theicct.org/publication/a-global-comparison-of-the-life-cycle-greenhouse-gas-emissions-of-combustion-engine-and-electric-passenger-cars/.

Blackman, A., and P. Veit. 2018. "Titled Amazon Indigenous Communities Cut Forest Carbon Emissions." *Ecological Economics* 153 (November): 56–67. doi:10.1016/j.ecolecon.2018.06.016.

Blackman, A., L. Corral, E.S. Lima, and G.P. Asner. 2017. "Titling Indigenous Communities Protects Forests in the Peruvian Amazon." *Proceedings of the National Academy of Sciences* 114 (16): 4123–28. doi:10.1073/pnas.1603290114.

Bliss, L. 2022. "Six States Adopt Clean Truck Rule." *Transport Topics*, January 6. https://www.ttnews.com/articles/six-states-adopt-clean-truck-rule.

BNEF (Bloomberg New Energy Finance). 2020. "Hydrogen: The Economics of Powering Ships." New York: BNEF. https://about.bnef.com/electricvehicle-outlook-2020/.

BNEF. 2021a. "2021 Lithium-Ion Battery Price Survey." New York: BNEF.

BNEF. 2021b. "Electric Vehicle Outlook 2021." New York: BNEF. https://about.bnef.com/electric-vehicle-outlook/.

BNEF. 2021c. "Sustainable Aviation Fuels (Part 1): Pathways to Production." New York: BNEF. https://about. bnef.com/new-energy-outlook/.

BNEF. 2021d. "Direct Air Capture of CO_2 to Increase 150-Fold by 2024." BNEF (blog), May 5. https://about.bnef.com/blog/direct-air-capture-of-co2-to-increase-150-fold-by-2024/.

BNEF. 2022a. "Electric Vehicle Outlook 2022." New York: BNEF. https://about.bnef.com/electric-vehicle-outlook/.

BNEF. 2022b. "Hydrogen—10 Predictions for 2022." BNEF (blog), January 21. https://about.bnef.com/blog/hydrogen-10-predictions-for-2022/.

BNEF. 2022c. "Gas & LNG—10 Predictions for 2022." BNEF (blog), January 27. https://about.bnef.com/blog/gas-lng-10-predictions-for-2022/.

Boehm, S., K. Lebling, K. Levin, H. Fekete, J. Jaeger, R. Waite, A. Nilsson, et al. 2021. *State of Climate Action 2021: Systems Transformations Required to Limit Global Warming to 1.5°C.* Washington, DC: World Resources Institute. https://www.wri.org/research/state-climate-action-2021.

Borenstein, S., and L.W. Davis. 2016. "The Distributional Effects of US Clean Energy Tax Credits." *Tax Policy and the Economy* 30 (1): 191–234. doi:10.1086/685597.

Bos, J., and J. Thwaites. 2021. "A Breakdown of Developed Countries' Public Climate Finance Contributions towards the $100 Billion Goal." Washington, DC: World Resources Institute. https://www.wri.org/research/breakdown-developed-countries-public-climate-finance-contributions-towards-100-billion.

Bossio, D.A., S.C. Cook-Patton, P.W. Ellis, J. Fargione, J. Sanderman, P. Smith, S. Wood, et al. 2020. "The Role of Soil Carbon in Natural Climate Solutions." *Nature Sustainability* 3 (5): 391–98. doi:10.1038/s41893-020-0491-z.

Boulton, C.A., T.M. Lenton, and N. Boers. 2022. "Pronounced Loss of Amazon Rainforest Resilience since the Early 2000s." *Nature Climate Change* 12 (3): 271–78. doi:10.1038/s41558-022-01287-8.

Bourgeau-Chavez, L.L., S.L. Endres, J.A. Graham, J.A. Hribljan, R.A. Chimner, E.A. Lillieskov, and M.J. Battaglia. 2018. "Mapping Peatlands in Boreal and Tropical Ecoregions." In *Comprehensive Remote Sensing*, edited by S. Liang, 6:24–44. Oxford, UK: Elsevier. http://www.fs.usda.gov/treesearch/pubs/58573.

Boyd, W., C. Stickler, A.E. Duchelle, F. Seymour, D. Nepstad, N.H.A. Bahar, and D. Rodriguez-Ward. 2018. "Ending Tropical Deforestation: Jurisdictional Approaches to REDD+ and Low Emissions Development: Progress and Prospects." Washington, DC: World Resources Institute. https://www.wri.org/research/ending-tropical-deforestation-jurisdictional-approaches-redd-and-low-emissions-development.

BP. 2021. "BP Statistical Review of World Energy." https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2021-full-report.pdf.

BPIE (Buildings Performance Institute Europe) and CLIMACT. 2021. "Lessons Learned to Inform Integrated Approaches for the Renovation and Modernisation of the Built Environment. Annex IV: Analysis of the Relevance, Feasibility and Possible Scope of Mandatory Minimum Requirements for Existing Buildings." ENER C3_2019-468_03. https://op.europa.eu/o/opportal-service/download-handler?identifier=e79af251-c419-11eb-a925-01aa75ed71a1&format=pdf&language=en&productionSystem=cellar&part=.

Bradsher, K., and J. Dong. 2022. "China's Record Drought Is Drying Rivers and Feeding Its Coal Habit." *New York Times*, August 26. https://www.nytimes.com/2022/08/26/business/economy/china-drought-economy-climate.html.

Breakthrough Energy. 2022. "The Catalyst Program." https://www.breakthroughenergy.org/scaling-innovation/catalyst.

BRGM (Badan Restorasi Gambut dan Mangrove [Peat Restoration Body, Indonesia]). 2021. "Gelar Refleksi Akhir Tahun, BRGM Ingin Capaian Tahun 2021 Berlanjut." December 13. https://ppid.brgm.go.id/siaranpers/gelar-refleksi-akhir-tahun-brgm-ingin-capaian-tahun-2021-berlanjut/.

Brulle, R.J. 2018. "The Climate Lobby: A Sectoral Analysis of Lobbying Spending on Climate Change in the USA, 2000 to 2016." *Climatic Change* 149 (3–4): 289–303. doi:10.1007/s10584-018-2241-z.

Buchner, B., B. Naran, P. de Aragão Fernandes, R. Padmanabhi, P. Rosane, M. Solomon, S. Stout, et al. 2021. "Global Landscape of Climate Finance 2021." London: Climate Policy Initiative. https://www.climatepolicyinitiative.org/publication/global-landscape-of-climate-finance-2021/.

Buckingham, K., and T. Ellersick. 2015. "The Restoration Diagnostic—Case Example: Nepal Community Forestry." Washington, DC: World Resources Institute. https://files.wri.org/d8/s3fs-public/WRI_Restoration_Diagnostic_Case_Example_Nepal.pdf.

Budiman, I., R.D. Hapsari, C.I. Wijaya, and E.N.N. Sari. 2021. "The Governance of Risk Management on Peatland: A Case Study of Restoration in South Sumatra, Indonesia." Jakarta: World Resources Institute Indonesia. https://wri-indonesia.org/en/publication/governance-risk-management-peatland.

Buhr, B., U. Volz, C. Donovan, G. Kling, Y. Lo, V. Murinde, and N. Pullin. 2018. "Climate Change and the Cost of Capital in Developing Countries." London: Imperial College London and SOAS University of London; Geneva: UN Environment Programme. http://unepinquiry.org/wp-content/uploads/2018/07/Climate_Change_and_the_Cost_of_Capital_in_Developing_Countries.pdf.

Bunting, P., A. Rosenqvist, L. Hilarides, R.M. Lucas, N. Thomas, T. Tadono, T.A. Worthington, et al. 2022. "Global Mangrove Extent Change, 1996–2020: Global Mangrove Watch Version 3.0." *Remote Sensing* 14 (15): 3657. doi:10.3390/rs14153657.

Busch, J., O. Amarjargal, F. Taheripour, K.G. Austin, R.N. Siregar, K. Koenig, and T.W. Hertel. 2022. "Effects of Demand-Side Restrictions on High-Deforestation Palm Oil in Europe on Deforestation and Emissions in Indonesia." *Environmental Research Letters* 17 (1): 014035. doi:10.1088/1748-9326/ac435e.

Butler-Sloss, S., K. Bond, and H. Benham. 2021. "Spiralling Disruption: The Feedback Loops of the Energy Transition." London: Carbon Tracker. https://carbontracker.org/reports/spiralling-disruption/.

Byers, E.A., G. Coxon, J. Freer, and J.W. Hall. 2020. "Drought and Climate Change Impacts on Cooling Water Shortages and Electricity Prices in Great Britain." *Nature Communications* 11 (1): 2239. doi:10.1038/s41467-020-16012-2.

Cabiyo, B., J.S. Fried, B.M. Collins, W. Stewart, J. Wong, and D.L. Sanchez. 2021. "Innovative Wood Use Can Enable Carbon-Beneficial Forest Management in California." *Proceedings of the National Academy of Sciences* 118 (49): e2019073118. doi:10.1073/pnas.2019073118.

California Climate Investments. 2021. "Clean Cars 4 All." https://www.caclimateinvestments.ca.gov/clean-cars-4-all.

Cambridge Econometrics and Element Energy. 2018. "Low-Carbon Cars in Europe: A Socio-economic Assessment." The Hague: European Climate Foundation. https://europeanclimate.org/resources/fuelling-europes-future-how-the-transition-from-oil-strengthens-the-economy/.

Canada and Germany. 2021. "Climate Finance Delivery Plan: Meeting the $100 Billion Goal." https://ukcop26.org/wp-content/uploads/2021/10/Climate-Finance-Delivery-Plan-1.pdf.

Cao, Z., E. Masanet, A. Tiwari, and S. Akolawala. 2021. "Decarbonizing Concrete: Deep Decarbonization Pathways for the Cement and Concrete Cycle in the United States, India, and China." Evanston, IL: ClimateWorks Foundation. https://www.climateworks.org/wp-content/uploads/2021/03/Decarbonizing_Concrete.pdf.

Capanna, S., J. Higdon, and M. Lackner. 2021. "Early Deployment of Direct Air Capture with Dedicated Geologic Storage." New York: Environmental Defense Fund. https://www.edf.org/sites/default/files/documents/DAC%20Policy_Final.pdf.

CAPCOA (*California* Air Pollution Control Officers Association). 2021. *Handbook for Analyzing Greenhouse Gas Emission Reductions, Assessing Climate Vulnerabilities, and Advancing Health and Equity*. Sacramento: CAPCOA. www.caleemod.com/handbook/index.html.

Cappelletti, F., J.-P. Vallar, and J. Wyssling. 2016. "The Energy Transition Chronicles." Besançon, France: energycities. https://energy-cities.eu/wp-content/uploads/2019/01/chroniqueste_complet_en.pdf.

Carattini, S., M. Carvalho, and S. Fankhauser. 2018. "Overcoming Public Resistance to Carbon Taxes." *WIREs Climate Change* 9 (5). doi:10.1002/wcc.531.

CarbonPlan. 2022. "CDR Database: CarbonPlan." https://carbonplan.org.

Carbon Pulse. 2021. "Key Govt Advisor Says Cement, Aluminium to Be Brought into China ETS in 2022." June 26. https://carbon-pulse.com/132444/.

Carley, S., and D. Konisky. 2020. "The Justice and Equity Implications of the Clean Energy Transition." *Nature Energy* 5: 569–77. doi:https://doi.org/10.1038/s41560-020-0641-6.

Carodenuto, S. 2019. "Governance of Zero Deforestation Cocoa in West Africa: New Forms of Public–Private Interaction." *Environmental Policy and Governance* 29 (1): 55–66. doi:10.1002/eet.1841.

Carpenter, S. 2021. "Rise of SUVs Complicates Efforts to Rein in Auto Emissions." *Forbes*, January 22. https://www.forbes.com/sites/scottcarpenter/2021/01/22/growing-popularity-of-suvs-complicates-efforts-to-reign-in-auto-emissions/.

Carrington, D. 2022. "South Africa's April Floods Made Twice as Likely by Climate Crisis, Scientists Say." *The Guardian*, May 13. https://www.theguardian.com/environment/2022/may/13/south-africa-floods-climate-crisis-global-heating.

Caulfield, B., D. Furszyfer, A. Stefaniec, and A. Foley. 2022. "Measuring the Equity Impacts of Government Subsidies for Electric Vehicles." *Energy* 248 (June): 123588. doi:10.1016/j.energy.2022.123588.

Cave, D. 2022. "'Can't Cope': Australia's Great Barrier Reef Suffers 6th Mass Bleaching Event." *New York Times*, March 25. https://www.nytimes.com/2022/03/25/world/australia/great-barrier-reef-bleaching.html.

CEFC (Clean Energy Finance Corporation). 2021. "SA Big Battery a Game Changer." Sydney, Australia: CEFC. https://www.cefc.com.au/where-we-invest/case-studies/sa-big-battery-a-game-changer/.

CER (Clean Energy Regulator). 2022. "History of the Scheme." Canberra, Australia: CER. http://www.cleanenergyregulator.gov.au/RET/About-the-Renewable-Energy-Target/History-of-the-scheme.

Chapin, F.S., S.R. Carpenter, G.P. Kofinas, C. Folke, N. Abel, W.C. Clark, P. Olsson, et al. 2010. "Ecosystem Stewardship: Sustainability Strategies for a Rapidly Changing Planet." *Trends in Ecology & Evolution* 25 (4): 241–49. doi:10.1016/j.tree.2009.10.008.

Chaturvedi, R., C. Hanson, H. Ding, and F. Seymour. 2019. "Public-Sector Measures to Conserve and Restore Forests: Overcoming Economic and Political Economy Barriers." Washington, DC: World Resources Institute. https://www.wri.org/research/public-sector-measures-conserve-and-restore-forests-overcoming-economic-and-political.

Chazdon, R.L., P.H.S. Brancalion, D. Lamb, L. Laestadius, M. Calmon, and C. Kumar. 2017. "A Policy-Driven Knowledge Agenda for Global Forest and Landscape Restoration." *Conservation Letters* 10 (1): 125–32. doi:10.1111/conl.12220.

Chen, C., R. Xu, D. Tong, X. Qin, J. Cheng, J. Liu, B. Zheng, L. Yan, and Q. Zhang. 2022. "A Striking Growth of CO_2 Emissions from the Global Cement Industry Driven by New Facilities in Emerging Countries." *Environmental Research Letters* 17 (4): 044007. doi:10.1088/1748-9326/ac48b5.

Cherp, A., V. Vinichenko, J. Tosun, J. Gordon, and J. Jewell. 2021. "National Growth Dynamics of Wind and Solar Power Compared to the Growth Required for Global Climate Targets." *Nature Energy* 6: 742–54. doi:https://doi.org/10.1038/s41560-021-00863-0.

Christiaensen, L., L. Demery, and J. Kuhl. 2011. "The (Evolving) Role of Agriculture in Poverty Reduction: An Empirical Perspective." *Journal of Development Economics* 96 (2): 239–54. doi:10.1016/j.jdeveco.2010.10.006.

City of Paris. 2021. "Un nouveau plan vélo pour une ville 100% cyclable." October 21. https://www.paris.fr/pages/un-nouveau-plan-velo-pour-une-ville-100-cyclable-19554.

Ciupuliga, A.R., and E. Cuppen. 2013. "The Role of Dialogue in Fostering Acceptance of Transmission Lines: The Case of a France-Spain Interconnection Project." *Energy Policy* 60 (September): 224–33. doi:10.1016/j.enpol.2013.05.028.

Clark, M.A., N.G.G. Domingo, K. Colgan, S.K. Thakrar, D. Tilman, J. Lynch, I.L. Azevedo, and J.D. Hill. 2020. "Global Food System Emissions Could Preclude Achieving the 1.5° and 2°C Climate Change Targets." *Science* 370 (6517): 705–8. doi:10.1126/science.aba7357.

Clifford, C. 2022. "These Scientists Bonded over Toilet Tech. Now They're Working on Carbon-Free Cement." CNBC, April 28. https://www.cnbc.com/2022/04/28/carbon-free-cement-breakthrough-dcvc-put-55-million-into-brimstone.html.

Climate Action Tracker. 2020a. "Paris Agreement Compatible Sectoral Benchmarks." Berlin: Climate Action Tracker. https://climateactiontracker.org/documents/754/CAT_2020-07-10_ParisAgreementBenchmarks_SummaryReport.pdf.

Climate Action Tracker. 2020b. "Paris Agreement Compatible Sectoral Benchmarks: Methods Report." Berlin: Climate Action Tracker. https://climateactiontracker.org/documents/753/CAT_2020-07-10_ParisAgreementBenchmarks_FullReport.pdf.

Climate Action Tracker. 2020c. "Paris Agreement Compatible Sectoral Benchmarks: Summary Report." Berlin: Climate Action Tracker. https://climateactiontracker.org/documents/754/CAT_2020-07-10_ParisAgreementBenchmarks_SummaryReport.pdf.

Climate Action Tracker. 2021. "Glasgow's 2030 Credibility Gap: Net Zero's Lip Service to Climate Action." Berlin: Climate Action Tracker. https://climateactiontracker.org/publications/glasgows-2030-credibility-gap-net-zeros-lip-service-to-climate-action/.

Climate Action Tracker. 2022a. "Decarbonising Buildings: Achieving Zero Carbon Heating and Cooling." Berlin: Climate Action Tracker. https://climateactiontracker.org/publications/decarbonising-buildings-achieving-net-zero-carbon-heating-and-cooling/.

Climate Action Tracker. 2022b. "ICAO Policies and Action." May 9. Berlin: Climate Action Tracker. https://climateactiontracker.org/sectors/aviation/policies-action/.

Climate Analytics. 2019. "Global and Regional Coal Phase-out Requirements of the Paris Agreement: Insights from the IPCC Special Report on 1.5°C." https://climateanalytics.org/media/report_coal_phase_out_2019.pdf.

Climate Analytics and WRI (World Resources Institute). 2021. "Closing the Gap: The Impact of G20 Climate Commitments on Limiting Global Temperature Rise to 1.5°C." Washington, DC: World Resources Institute; Berlin: Climate Analytics. https://www.wri.org/research/closing-the-gap-g20-climate-commitments-limiting-global-temperature-rise.

Climate Focus. 2022. "Voluntary Carbon Market Dashboard." Amsterdam: Climate Focus. https://climatefocus.com/initiatives/voluntary-carbon-market-dashboard/.

ClimateWatch. 2022. "Historical GHG Emissions." https://www.climatewatchdata.org/ghg-emissions?end_year=2019&start_year=1990.

Climeworks. 2021. "Orca Is Climeworks' New Large-Scale Carbon Dioxide Removal Plant." https://climeworks.com/roadmap/orca.

Climeworks. 2022a. "Groundbreaking on Climeworks' Newest Facility Has Started." https://climeworks.com/news/climeworks-announces-groundbreaking-on-mammoth.

Climeworks. 2022b. "Climeworks Raises CHF 600 Million (US $650 Million) in Equity." May 4. https://climeworks.com/news/equity-fundraising.

Coady, D., I. Parry, L. Sears, and B. Shang. 2017. "How Large Are Global Fossil Fuel Subsidies?" *World Development* 91 (March): 11–27. doi:10.1016/j.worlddev.2016.10.004.

Coalition for Urban Transitions. 2019. "Climate Emergency, Urban Opportunity." Washington, DC: Coalition for Urban Transitions. https://urbantransitions.global/en/publication/climate-emergency-urban-opportunity/.

Coleman, J. 2022. "Climate Change Made South Asian Heatwave 30 Times More Likely." *Nature*, May. doi:10.1038/d41586-022-01444-1.

Collins, L. 2022. “Ukraine War: Green Hydrogen ‘Now Cheaper than Grey in Europe, Middle East and China’: BNEF.” *Recharge: Latest Renewable Energy News*, March 7. https://www.rechargenews.com/energy-transition/ukraine-war-green-hydrogen-now-cheaper-than-grey-in-europe-middle-east-and-china-bnef/2-1-1180320.

Conant, R.T., C.E.P. Cerri, B.B. Osborne, and K. Paustian. 2017. “Grassland Management Impacts on Soil Carbon Stocks: A New Synthesis.” *Ecological Applications* 27 (2): 662–68. doi:10.1002/eap.1473.

Conchedda, G., and F.N. Tubiello. 2020. “Drainage of Organic Soils and GHG Emissions: Validation with Country Data.” *Earth System Science Data* 12 (4): 3113–37. doi:10.5194/essd-12-3113-2020.

Cook-Patton, S.C., C.R. Drever, B.W. Griscom, K. Hamrick, H. Hardman, T. Kroeger, P. Pacheco, et al. 2021. “Protect, Manage and Then Restore Lands for Climate Mitigation.” *Nature Climate Change* 11 (12): 1027–34. doi:10.1038/s41558-021-01198-0.

Cooling Post. 2022. “Austria to Ban Gas Boilers from 2023.” June 18. https://www.coolingpost.com/world-news/austria-to-ban-gas-boilers-from-2023/.

“COP26 Declaration on Accelerating the Transition to 100% Zero Emission Cars and Vans.” 2022. https://www.gov.uk/government/publications/cop26-declaration-zero-emission-cars-and-vans/cop26-declaration-on-accelerating-the-transition-to-100-zero-emission-cars-and-vans.

“COP26 IPLC Forest Tenure Joint Donor Statement.” 2021. UN Climate Change Conference UK 2021. November 2. https://ukcop26.org/cop26-iplc-forest-tenure-joint-donor-statement/.

COP26 Presidency. 2021. “Statement on International Public Support for the Clean Energy Transition.” https://ukcop26.org/statement-on-international-public-support-for-the-clean-energy-transition/.

Copman, L. 2021. “CALS Dean Ben Houlton May Have a Billion-Ton Solution to Climate Change.” *Alumni, Parents, and Friends: Cornell University* (blog), February 25. https://alumni.cornell.edu/article/cals-dean-ben-houlton-may-have-a-billion-ton-solution-to-climate-change/.

Costanza, R., R. de Groot, P. Sutton, S. van der Ploeg, S.J. Anderson, I. Kubiszewski, S. Farber, and R.K. Turner. 2014. “Changes in the Global Value of Ecosystem Services.” *Global Environmental Change* 26 (May): 152–58. doi:10.1016/j.gloenvcha.2014.04.002.

Cozzi, L., and B. Motherway. 2021. “The Importance of Focusing on Jobs and Fairness in Clean Energy Transitions.” International Energy Agency, July 6. https://www.iea.org/commentaries/the-importance-of-focusing-on-jobs-and-fairness-in-clean-energy-transitions.

CPI (Climate Policy Initiative). 2021. “Global Landscape of Climate Finance 2021 Methodology.” London: CPI. https://www.climatepolicyinitiative.org/wp-content/uploads/2021/10/Methodology.pdf.

CREA (Centre for Research on Energy and Clean Air) and Global Energy Monitor. 2021. “China’s Power & Steel Firms Continue to Invest in Coal Even as Emissions Surge Cools Down.” https://energyandcleanair.org/wp/wp-content/uploads/2021/08/China-Q2-briefing-coal-steel-CO2.pdf.

Creutzig, F., K.-H. Erb, H. Haberl, C. Hof, C. Hunsberger, and S. Roe. 2021. “Considering Sustainability Thresholds for BECCS in IPCC and Biodiversity Assessments.” *GCB Bioenergy* 13 (4): 510–15. doi:10.1111/gcbb.12798.

Cronin, J., G. Anandarajah, and O. Dessens. 2018. “Climate Change Impacts on the Energy System: A Review of Trends and Gaps.” *Climatic Change* 151 (2): 79–93. doi:10.1007/s10584-018-2265-4.

Crozier, C. 2020. “Forecasting S-Curves Is Hard.” Blog, April 16. https://constancecrozier.com/2020/04/16/forecasting-s-curves-is-hard/.

Crump, J. 2017. “Smoke on Water: Countering Global Threats from Peatland Loss and Degradation.” Nairobi: UN Environment Programme; Arendal, Norway: GRID-Arendal. https://gridarendal-website-live.s3.amazonaws.com/production/documents/:s_document/376/original/RRApeatland_revised_jan.pdf?1515398975.

Cui, H., P. Gode, and S. Wappelhorst. 2021. “A Global Overview of Zero-Emission Zones in Cities and Their Development Progress.” Washington, DC: International Council on Clean Transportation. https://theicct.org/publication/a-global-overview-of-zero-emission-zones-in-cities-and-their-development-progress/.

Curran, G. 2020. “Divestment, Energy Incumbency and the Global Political Economy of Energy Transition: The Case of Adani’s Carmichael Mine in Australia.” *Climate Policy* 20 (8): 949–62. doi:10.1080/14693062.2020.1756731.

Currie & Brown and AECOM (Architecture, Engineering, Construction, Operations, and Management). 2019. *The Costs and Benefits of Tighter Standards for New Buildings*. London: Committee on Climate Change. https://www.theccc.org.uk/publication/the-costs-and-benefits-of-tighter-standards-for-new-buildings-currie-brown-and-aecom/.

Curtis, P.G., C.M. Slay, N.L. Harris, A. Tyukavina, and M.C. Hansen. 2018. “Classifying Drivers of Global Forest Loss.” *Science* 361 (6407): 1108–11. doi:10.1126/science.aau3445.

Czapiewski, S., and D. Szumińska. 2021. “An Overview of Remote Sensing Data Applications in Peatland Research Based on Works from the Period 2010–2021.” *Land* 11 (1): 24. doi:10.3390/land11010024.

Dadzie, J., G. Runeson, G. Ding, and F.K. Bondinuba. 2018. “Barriers to Adoption of Sustainable Technologies for Energy-Efficient Building Upgrade: Semi-structured Interviews.” *Buildings* 8 (4): 57. doi:10.3390/buildings8040057.

Dasgupta, S., and E.J.Z. Robinson. 2022. “Impact of COVID-19 on Food Insecurity Using Multiple Waves of High Frequency Household Surveys.” *Scientific Reports* 12 (1): 1865. doi:10.1038/s41598-022-05664-3.

Davis, J. 2021. "Explainer: What the '80-20 Highway-Transit Split' Really Is, and What It Isn't." *Eno Transportation Weekly* (blog), July 26. https://www.enotrans.org/article/explainer-what-the-80-20-highway-transit-split-really-is-and-what-it-isnt/.

Davis, S.J., Z. Liu, Z. Deng, B. Zhu, P. Ke, T. Sun, R. Guo, et al. 2022. "Emissions Rebound from the COVID-19 Pandemic." *Nature Climate Change*, March. doi:https://doi.org/10.1038/s41558-022-01332-6.

Day, T., S. Mooldjik, S. Smit, E. Posada, F. Hans, H. Fearnehough, A. Kachi, et al. 2022. "Corporate Climate Responsibility Monitor 2022." NewClimate Institute. https://newclimate.org/sites/default/files/2022-06/CorporateClimateResponsibilityMonitor2022.pdf.

Defiance ETFs. 2022. "Green Hydrogen's Strong Outlook for 2022." February 11. https://www.defianceetfs.com/green-hydrogens-strong-outlook-for-2022/#_ftn17.

Deign, J. 2021. "How Much Renewables Expansion Is Needed for a Global Green Hydrogen?" *Canary Media* (blog), July 13. https://www.canarymedia.com/articles/hydrogen/how-much-renewable-capacity-would-world-need-for-green-hydrogen.

Deloitte. n.d. "Teaming Up with Top Airlines for Sustainable Fuel." *Deloitte* (blog). https://www2.deloitte.com/us/en/pages/about-deloitte/articles/sustainable-aviation-fuel-agreements.html.

Dennis, M. 2021. "Are We on the Brink of an Electric Vehicle Boom? Only with More Action." World Resources Institute (blog), September 16. https://www.wri.org/insights/what-projected-growth-electric-vehicles-adoption.

Department for Energy and Mining. 2022. "Leading the Green Economy." Adelaide: Government of South Australia. https://www.energymining.sa.gov.au/growth_and_low_carbon/leading_the_green_economy.

de Pee, A., D. Pinner, R. Occo, K. Somers, M. Witteveen, and E. Speelman. 2018. "Decarbonization of Industrial Sectors: The Next Frontier." New York: McKinsey & Company. https://www.mckinsey.com/~/media/mckinsey/business%20functions/sustainability/our%20insights/how%20industry%20can%20move%20toward%20a%20low%20carbon%20future/decarbonization-of-industrial-sectors-the-next-frontier.pdf.

Dinesh, D. 2017. "10 Best Bet Innovations for Adaptation in Agriculture: A Supplement to the UNFCCC NAP Technical Guidelines." CCAFS Working Paper 215. CGIAR Research Program on Climate Change, Agriculture, and Food Security (CCAFS). www.ccafs.cgiar.org.

Ding, H., P. Veit, E. Gray, K. Reytar, J.-C. Altamirano, and A. Blackman. 2016. "Climate Benefits, Tenure Costs: The Economic Case for Securing Indigenous Land Rights." Washington, DC: World Resources Institute. https://www.wri.org/research/climate-benefits-tenure-costs.

Ding, H., S. Faruqi, A. Wu, J.C. Altamirano, A.A. Ortega, M. Verdone, R.Z. Cristales, et al. 2017. "The Economics and Finance of Restoring Land." Washington, DC: World Resources Institute. https://www.wri.org/research/roots-prosperity-economics-and-finance-restoring-land.

Di Sacco, A., K.A. Hardwick, D. Blakesley, P.H.S. Brancalion, E. Breman, L. Cecilio Rebola, S. Chomba, et al. 2021. "Ten Golden Rules for Reforestation to Optimize Carbon Sequestration, Biodiversity Recovery and Livelihood Benefits." *Global Change Biology* 27 (7): 1328–48. doi:10.1111/gcb.15498.

Djenontin, I., S. Foli, and L. Zulu. 2018. "Revisiting the Factors Shaping Outcomes for Forest and Landscape Restoration in Sub-Saharan Africa: A Way forward for Policy, Practice and Research." *Sustainability* 10 (4): 906. doi:10.3390/su10040906.

Dohong, A., A.A. Aziz, and P. Dargusch. 2017. "A Review of the Drivers of Tropical Peatland Degradation in South-East Asia." *Land Use Policy* 69 (December): 349–60. doi:10.1016/j.landusepol.2017.09.035.

Dohong, A., A. Abdul Aziz, and P. Dargusch. 2018. "A Review of Techniques for Effective Tropical Peatland Restoration." *Wetlands* 38 (2): 275–92. doi:10.1007/s13157-018-1017-6.

Du, P., L.-Q. Zheng, B.-C. Xie, and A. Mahalingam. 2014. "Barriers to the Adoption of Energy-Saving Technologies in the Building Sector: A Survey Study of Jing-Jin-Tang, China." *Energy Policy* 75 (December): 206–16. doi:10.1016/j.enpol.2014.09.025.

Dubash, N.K. 2021. "Varieties of Climate Governance: The Emergence and Functioning of Climate Institutions." *Environmental Politics* 30 (suppl. 1): 1–25. doi:10.1080/09644016.2021.1979775.

Dufour, L., B. Tucker, L. van der Burg, M. Hendriwardani, and A. Geddes. 2022. "Turning Pledges into Action: How Glasgow Statement Signatories Can Meet Their Commitment to Shift International Public Finance Out of Fossil Fuels and into Clean Energy by the End of 2022." Winnipeg, Canada: International Institute for Sustainable Development. https://www.iisd.org/system/files/2022-06/turning-glasgow-statement-into-action.pdf.

Dummett, C., A. Blundell, K. Canby, M. Wolosin, and E. Bodnar. 2021. "Illicit Harvest, Complicit Goods: The State of Illegal Deforestation for Agriculture." Washington, DC: Forest Trends. https://www.forest-trends.org/publications/illicit-harvest-complicit-goods.

Duncan, B.N., L.N. Lamsal, A.M. Thompson, Y. Yoshida, Z. Lu, D.G. Streets, M.M. Hurwitz, and K.E. Pickering. 2016. "A Space-Based, High-Resolution View of Notable Changes in Urban NO_x Pollution around the World (2005–2014): Notable Changes in Urban NO_x Pollution." *Journal of Geophysical Research: Atmospheres* 121 (2): 976–96. doi:10.1002/2015JD024121.

Dunn, A., and T. Van Green. 2021. "Top Tax Frustrations for Americans: The Feeling That Some Corporations, Wealthy People Don't Pay Fair Share." Pew Research Center. https://www.pewresearch.org/fact-tank/2021/04/30/top-tax-frustrations-for-americans-the-feeling-that-some-corporations-wealthy-people-dont-pay-fair-share/.

Economidou, M., V. Todeschi, P. Bertoldi, D. D'Agostino, P. Zangheri, and L. Castellazzi. 2020. "Review of 50 Years of EU Energy Efficiency Policies for Buildings." *Energy and Buildings* 225 (October): 110322. doi:10.1016/j.enbuild.2020.110322.

Ekawati, S., Subarudi, K. Budiningsih, G.K. Sari, and M.Z. Muttaqin. 2019. "Policies Affecting the Implementation of REDD+ in Indonesia (Cases in Papua, Riau and Central Kalimantan)." *Forest Policy and Economics* 108 (November): 101939. doi:10.1016/j.forpol.2019.05.025.

Ellis, B., and W. Bao. 2020. “Pathways to Decarbonisation, Episode Two: Steelmaking Technology.” 2020. https://www.bhp.com/news/prospects/2020/11/pathways-to-decarbonisation-episode-two-steelmaking-technology.

Eltis. 2022. “Case Studies.” https://www.eltis.org/resources/case-studies.

Ember. 2022. “Global Electricity Review.” London: Ember. https://ember-climate.org/insights/research/global-electricity-review-2022/.

Energy Systems Catapult. 2021. “Thinking Electricity Markets.” Birmingham, UK: Energy Systems Catapult. https://es.catapult.org.uk/report/rethinking-electricity-markets-the-case-for-emr-2/?reportDownload=https://esc-production-2021.s3.eu-west-2.amazonaws.com/2021/09/ESC-Rethinking-Electricty-Markets-Report-Final-Pages.pdf.

Englert, D., and A. Losos. 2021. “Charting a Course for Decarbonizing Maritime Transport: Summary for Policymakers and Industry.” Washington, DC: World Bank. https://openknowledge.worldbank.org/handle/10986/35436.

EPOMM (European Platform on Mobility Management). n.d. “Case Studies.” https://epomm.eu/archive/maxlupo/case-studies.

Essers, D., D. Cassimon, and M. Prowse. 2021. “Debt-for-Climate Swaps: Killing Two Birds with One Stone?” *Global Environmental Change* 71 (November): 102407. doi:10.1016/j.gloenvcha.2021.102407.

ETC (Energy Transitions Commission). 2018a. “Reaching Net-Zero Carbon Emissions from Harder-to-Abate Sectors by Mid-century.” https://www.energy-transitions.org/publications/mission-possible/#:~:text=The%20report%20Mission%20Possible%3A%20Reaching,60%25%20by%20mid%2Dcentury%20as.

ETC. 2018b. “Mission Possible—Sectoral Focus: Building Heating.” https://www.energy-transitions.org/wp-content/uploads/2020/08/200729-ETC-Paper-Building-Heating-FINAL.pdf.ETC.

ETC. 2019a. “Mission Possible—Sectoral Focus: Cement.” https://www.energy-transitions.org/publications/mission-possible-sectoral-focus-cement/#download-form.

ETC. 2019b. “Mission Possible—Sectoral Focus: Aviation.” https://www.energy-transitions.org/publications/mission-possible-sectoral-focus-aviation/.

ETC. 2019c. “Mission Possible—Sectoral Focus: Shipping.” https://www.energy-transitions.org/publications/mission-possible-sectoral-focus-shipping/.

ETC. 2020. “Making Mission Possible: Delivering a Net-Zero Economy.” https://www.energy-transitions.org/wp-content/uploads/2020/09/Making-Mission-Possible-Executive-Summary-English.pdf.

ETC. 2021. “Mission Possible: Reaching Net-Zero Carbon Emissions from Harder-to-Abate Sectors by Mid-century—Sectoral Focus: Shipping.” https://www.energy-transitions.org/wp-content/uploads/2020/08/ETC-sectoral-focus-Shipping_final.pdf.

ETC. 2022. “Mind the Gap: How Carbon Dioxide Removals Must Complement Deep Decarbonisation to Keep 1.5°C Alive.” https://www.energy-transitions.org/publications/mind-the-gap-cdr/.

EU (European Union). 2021a. “Funding & Tenders: Carbon Dioxide Removal Approaches.” https://ec.europa.eu/info/funding-tenders/opportunities/portal/screen/opportunities/topic-details/horizon-cl5-2022-d1-01-01-two-stage.

EU. 2021b. “Proposals to Remove, Recycle and Sustainably Store Carbon.” European Commission. https://ec.europa.eu/commission/presscorner/detail/en/IP_21_6687.

European Alternative Fuels Observatory. 2022. “Transport Modes: Road.” https://alternative-fuels-observatory.ec.europa.eu/transport-mode/road.

European Commission. 2021a. “European Green Deal: Commission Proposes to Boost Renovation and Decarbonisation of Buildings.” https://ec.europa.eu/commission/presscorner/detail/en/ip_21_6683.

European Commission. 2021b. “Proposal for a Directive of the European Parliament and of the Council Amending Directive 2003/87/EC as Regards Aviation’s Contribution to the Union’s Economy-wide Emission Reduction Target and Appropriately Implementing a Global Market-Based Measure.” https://ec.europa.eu/transparency/documents-register/detail?ref=COM(2021)552&lang=en.

European Commission. 2022a. “EU Buildings Database.” https://ec.europa.eu/energy/eu-buildings-database_en.

European Commission. 2022b. “EU Taxonomy: Complementary Climate Delegated Act to Accelerate Decarbonisation.” February. https://finance.ec.europa.eu/publications/eu-taxonomy-complementary-climate-delegated-act-accelerate-decarbonisation_en#files.

European Council. 2022. “Infographic—Fit for 55: Increasing the Uptake of Greener Fuels in the Aviation and Maritime Sectors.” July 14. https://www.consilium.europa.eu/en/infographics/fit-for-55-refueleu-and-fueleu/.

Evans, M.C. 2018. “Effective Incentives for Reforestation: Lessons from Australia’s Carbon Farming Policies.” *Current Opinion in Environmental Sustainability* 32 (June): 38–45. doi:10.1016/j.cosust.2018.04.002.

Evers, S., C.M. Yule, R. Padfield, P. O’Reilly, and H. Varkkey. 2017. “Keep Wetlands Wet: The Myth of Sustainable Development of Tropical Peatlands—Implications for Policies and Management.” *Global Change Biology* 23 (2): 534–49. doi:10.1111/gcb.13422.

Fa, J.E., J.E. Watson, I. Leiper, P. Potapov, T.D. Evans, N.D. Burgess, Z. Molnár, et al. 2020. “Importance of Indigenous Peoples’ Lands for the Conservation of Intact Forest Landscapes.” *Frontiers in Ecology and the Environment* 18 (3): 135–40. doi:10.1002/fee.2148.

Fan, Z., H. Sheerati, A. Bhardwaj, A.-S. Corbeau, K. Longobardi, C.M. Woodall, M. Agrawal, et al. 2022. “Hydrogen Leakage: A Potential Risk for the Hydrogen Economy.” https://www.energypolicy.columbia.edu/research/commentary/hydrogen-leakage-potential-risk-hydrogen-economy.

FAO (Food and Agriculture Organization of the United Nations). 2019. "The State of Food and Agriculture 2019: Moving Forward on Food Loss and Waste Reduction." Rome: FAO. http://www.fao.org/3/ca6030en/ca6030en.pdf.

FAO. 2020. "Peatlands Mapping and Monitoring: Recommendations and Technical Overview." Rome: FAO. https://doi.org/10.4060/ca8200en.

FAO. 2021. "The Share of Food Systems in Total Greenhouse Gas Emissions: Global, Regional and Country Trends, 1990–2019." FAOSTAT Analytical Brief Series. Rome: FAO. https://www.fao.org/food-agriculture-statistics/data-release/data-release-detail/en/c/1454718/.

FAO. 2022a. "Emissions from Agriculture and Forest Land." FAOSTAT Analytical Brief Series. Rome: FAO. https://www.fao.org/3/cb5293en/cb5293en.pdf.

FAO. 2022b. *In Brief to "The State of Food Security and Nutrition in the World 2022": Repurposing Food and Agricultural Policies to Make Healthy Diets More Affordable.* Rome: FAO, International Fund for Agricultural Development, UN Children's Fund, World Food Programme, and World Health Organization. doi:10.4060/cc0640en.

FAO and FILAC (Fund for the Development of the Indigenous Peoples of Latin America and the Caribbean). 2021. *Forest Governance by Indigenous and Tribal Peoples: An Opportunity for Climate Action in Latin America and the Caribbean.* Rome: FAO. doi:10.4060/cb2953en.

FAO, International Fund for Agricultural Development, UN Children's Fund, World Food Programme, and World Health Organization. 2021. *The State of Food Security and Nutrition in the World 2021: Transforming Food Systems for Food Security, Improved Nutrition and Affordable Healthy Diets for All.* Rome: FAO. https://doi.org/10.4060/cb4474en.

FAO and UNCCD (UN Convention to Combat Desertification). 2015. "Sustainable Financing for Forest and Landscape Restoration: Opportunities, Challenges and the Way Forward." Rome: FAO and UNCCD. http://www.fao.org/3/I5174E/i5174e.pdf.

FAO and UNEP (UN Environment Programme). 2020. *State of the World's Forests 2020: Forestry, Biodiversity and People.* State of the World's Forests 2020. Rome: FAO and UNEP. http://www.fao.org/documents/card/en/c/ca8642en/#:~:text=The%20State%20of%20the%20World's%20Forests%202020%20assesses%20progress%20to,conservation%20and%20sustainable%20development%20outcomes.

FAOSTAT. 2022. "FAOSTAT Data." Rome: FAO. http://www.fao.org/faostat/en/#data.

Ferdinand, T., E. Illick-Frank, L. Postema, J. Stephenson, A. Rose, D. Petrovic, C. Migisha, et al. 2021. "A Blueprint for Digital Climate-Informed Advisory Services: Building the Resilience of 300 Million Small-Scale Producers by 2030." July. https://www.wri.org/research/digital-climate-informed-advisory-services.

Few, R., D. Morchain, D. Spear, A. Mensah, and R. Bendapudi. 2017. "Transformation, Adaptation and Development: Relating Concepts to Practice." *Palgrave Communications* 3 (1): 17092. doi:10.1057/palcomms.2017.92.

Feyertag, J., M. Childress, R. Flynn, I. Langdown, A. Locke, and D. Nizalov. 2020. "Prindex Comparative Report 2020: A Global Assessment of Perceived Tenure Security from 140 Countries." London: Prindex. https://www.prindex.net/reports/prindex-comparative-report-july-2020/.

Finer, M., S. Novoa, M.J. Weisse, R. Petersen, J. Mascaro, T. Souto, F. Stearns, and R.G. Martinez. 2018. "Combating Deforestation: From Satellite to Intervention." *Science* 360 (6395): 1303–5. doi:10.1126/science.aat1203.

First Movers Coalition. 2022. "Mobilizing Collective Demand for Emerging Clean Technologies." World Economic Forum. 2022. https://www.weforum.org/first-movers-coalition/.

Fischhendler, I., L. Herman, and L. David. 2022. "Light at the End of the Panel: The Gaza Strip and the Interplay between Geopolitical Conflict and Renewable Energy Transition." *New Political Economy* 27 (1): 1–18. doi:10.1080/13563467.2021.1903850.

Fleming, S. 2021. "Electric Bike Sales Grew by 145% in the US Last Year—Here's Why That Matters." World Economic Forum (blog), March 12. https://www.weforum.org/agenda/2021/03/electric-bicycles-sales-growth/.

Folke, C., S. Carpenter, B. Walker, M. Scheffer, T. Chapin, and J. Rockström. 2010. "Resilience Thinking: Integrating Resilience, Adaptability and Transformability." *Ecology and Society* 15 (4). doi:10.5751/ES-03610-150420.

Forest 500. 2022a. "Company Assessment Methodology 2022." Oxford, UK: Global Canopy. https://forest500.org/sites/default/files/forest_500_company_assessment_methodology_2022.pdf.

Forest 500. 2022b. "A Climate Wake-Up: But Business Failing to Hear the Alarm on Deforestation." Oxford, UK: Global Canopy. https://forest500.org/publications/climate-wake-business-failing-hear-alarm-deforestation.

Fountain, H. 2022. "In a First, an Ice Shelf Collapses in East Antarctica." *New York Times*, March 25. https://www.nytimes.com/2022/03/25/climate/east-antarctica-ice-shelf-collapse.html.

Fourqurean, J.W., C.M. Duarte, H. Kennedy, N. Marbà, M. Holmer, M.A. Mateo, E.T. Apostolaki, et al. 2012. "Seagrass Ecosystems as a Globally Significant Carbon Stock." *Nature Geoscience* 5 (7): 505–9. doi:10.1038/ngeo1477.

Frangoul, A. 2021. "Maersk Spends $1.4 Billion on Ships That Can Run on 'Carbon Neutral' Methanol." CNBC, August 24. https://www.cnbc.com/2021/08/24/maersk-spends-1point4-billion-on-ships-that-can-run-on-methanol.html.

Fransen, T., K. Lebling, D. Weyl, and K. Kennedy. 2021. "Toward a Tradable Low-Carbon Cement Standard: Policy Design Considerations for the United States." World Resources Institute. doi:10.46830/wriwp.20.00112.

Fraser, C. 2022. "Community Benefits Agreements Offer Meaningful Opportunities to Include Voters' Voices in Development." Data for Progress. https://www.dataforprogress.org/blog/2022/7/5/community-benefits-agreements-offer-meaningful-opportunities-to-include-voters-voices-in-development.

Fraunhofer IAO (Institute for Industrial Engineering). 2020. "Employment 2030: Effects of Electric Mobility and Digitalisation on the Quality and Quantity of Employment at Volkswagen." Stuttgart: Fraunhofer IAO. https://www.volkswagenag.com/en/news/stories/2020/12/fraunhofer-study--employment-at-volkswagen-in-2030.html.

Fresnillo, I. 2020. "A Tale of Two Emergencies: The Interplay of Sovereign Debt and Climate Crises in the Global South." Brussels: Eurodad. https://www.eurodad.org/a_tale_of_two_emergencies_the_interplay_of_sovereign_debt_and_climate_crises_in_the_global_south.

Friedlingstein, P., M.W. Jones, M. O'Sullivan, R.M. Andrew, D.C.E. Bakker, J. Hauck, C. Le Quéré, et al. 2022. "Global Carbon Budget 2021." *Earth System Science Data* 14 (4): 1917–2005. doi:10.5194/essd-14-1917-2022.

Friess, D.A., B.S. Thompson, B. Brown, A.A. Amir, C. Cameron, H.J. Koldewey, S.D. Sasmito, and F. Sidik. 2016. "Policy Challenges and Approaches for the Conservation of Mangrove Forests in Southeast Asia: Conservation of Mangrove Forests." *Conservation Biology* 30 (5): 933–49. doi:10.1111/cobi.12784.

Friess, D.A., K. Rogers, C.E. Lovelock, K.W. Krauss, S.E. Hamilton, S.Y. Lee, R. Lucas, et al. 2019. "The State of the World's Mangrove Forests: Past, Present, and Future." *Annual Review of Environment and Resources* 44 (1): 89–115. doi:10.1146/annurev-environ-101718-033302.

Frontier. 2022. "An Advance Market Commitment to Accelerate Carbon Removal." https://frontierclimate.com/.

Furumo, P.R., and E.F. Lambin. 2020. "Scaling Up Zero-Deforestation Initiatives through Public-Private Partnerships: A Look inside Post-conflict Colombia." *Global Environmental Change* 62 (May): 102055. doi:10.1016/j.gloenvcha.2020.102055.

Fuss, S., and F. Johnsson. 2021. "The BECCS Implementation Gap: A Swedish Case Study." *Frontiers in Energy Research* 8. https://www.frontiersin.org/article/10.3389/fenrg.2020.553400.

Fuss, S., W.F. Lamb, M.W. Callaghan, J. Hilaire, F. Creutzig, T. Amann, T. Beringer, et al. 2018. "Negative Emissions—Part 2: Costs, Potentials and Side Effects." *Environmental Research Letters* 13 (6): 063002. doi:10.1088/1748-9326/aabf9f.

Fyson, C.L., S. Baur, M. Gidden, and C.-F. Schleussner. 2020. "Fair-Share Carbon Dioxide Removal Increases Major Emitter Responsibility." *Nature Climate Change* 10 (9): 836–41. doi:10.1038/s41558-020-0857-2.

Gallagher, K., and R. Kozul-Wright. 2019. "A New Multilateralism for Shared Prosperity: Geneva Principles for a Global Green New Deal." Boston; Geneva, Switzerland: Global Development Policy Center, Boston University; United Nations Conference on Trade and Development. https://www.bu.edu/gdp/files/2019/05/Updated-New-Graphics-New-Multilateralism-May-8-2019.pdf.

Garrett, R.D., S. Levy, K.M. Carlson, T.A. Gardner, J. Godar, J. Clapp, P. Dauvergne, et al. 2019. "Criteria for Effective Zero-Deforestation Commitments." *Global Environmental Change* 54 (January): 135–47. doi:10.1016/j.gloenvcha.2018.11.003.

Gatti, L.V., L.S. Basso, J.B. Miller, M. Gloor, L. Gatti Domingues, H.L.G. Cassol, G. Tejada, et al. 2021. "Amazonia as a Carbon Source Linked to Deforestation and Climate Change." *Nature* 595 (7867): 388–93. doi:10.1038/s41586-021-03629-6.

Gaur, A.S., D.Z. Fitiwi, and J. Curtis. 2021. "Heat Pumps and Our Low-Carbon Future: A Comprehensive Review." *Energy Research & Social Science* 71 (January): 101764. doi:10.1016/j.erss.2020.101764.

Gaveau, D.L.A., R. Pirard, M.A. Salim, P. Tonoto, H. Yaen, S.A. Parks, and R. Carmenta. 2017. "Overlapping Land Claims Limit the Use of Satellites to Monitor No-Deforestation Commitments and No-Burning Compliance." *Conservation Letters* 10 (2): 257–64. doi:10.1111/conl.12256.

GCCA (Global Cement and Concrete Association). 2021. "Getting the Numbers Right." GNR–GCCA in Numbers. https://gccassociation.org/sustainability-innovation/gnr-gcca-in-numbers/.

Geddes, A., I. Gerasimchuk, B. Viswanathan, A. Picciariello, B. Tucker, A. Doukas, V. Corkal, et al. 2020. "Doubling Back and Doubling Down: G20 Scorecard on Fossil Fuel Funding." Winnipeg; London; Washington, DC: International Institute for Sustainable Development; Overseas Development Institute; Oil Change International. https://www.iisd.org/publications/g20-scorecard.

Geels, F.W., and J. Schot. 2007. "Typology of Sociotechnical Transition Pathways." *Research Policy* 36 (3): 399–417. doi:10.1016/j.respol.2007.01.003.

Geels, F.W., B.K. Sovacool, T. Schwanen, and S. Sorrell. 2017. "The Socio-technical Dynamics of Low-Carbon Transitions." *Joule* 1 (3): 463–79. doi:10.1016/j.joule.2017.09.018.

Gensler, G. 2022. "Statement on Proposed Mandatory Climate Risk Disclosures." U.S. Securities and Exchange Commission, March 21. https://www.sec.gov/news/statement/gensler-climate-disclosure-20220321.

GFANZ (Glasgow Financial Alliance for Net Zero). 2021. "The Glasgow Financial Alliance for Net Zero: Our Progress and Plan towards a Net-Zero Global Economy." Glasgow: GFANZ. https://www.gfanzero.com/progress-report/.

GFI (Good Food Institute). 2021. "The Science of Cultivated Meat." January 27. https://gfi.org/science/the-science-of-cultivated-meat/.

Gibson, L., T.M. Lee, L.P. Koh, B.W. Brook, T.A. Gardner, J. Barlow, C.A. Peres, et al. 2011. "Primary Forests Are Irreplaceable for Sustaining Tropical Biodiversity." *Nature* 478 (7369): 378–81. doi:10.1038/nature10425.

Giri, C., E. Ochieng, L.L. Tieszen, Z. Zhu, A. Singh, T. Loveland, J. Masek, and N. Duke. 2011. "Status and Distribution of Mangrove Forests of the World Using Earth Observation Satellite Data: Status and Distributions of Global Mangroves." *Global Ecology and Biogeography* 20 (1): 154–59. doi:10.1111/j.1466-8238.2010.00584.x.

GIZ (German development agency). 2020. "New Energy Buses in China: Overview on Policies and Impacts." Beijing: GIZ. https://www.changing-transport.org/wp-content/uploads/2020_GIZ_New-Energy-Buses-in-China.pdf.

"Glasgow Leaders' Declaration on Forests and Land Use." 2021. UN Climate Change Conference UK 2021. November 2. https://ukcop26.org/glasgow-leaders-declaration-on-forests-and-land-use/.

GlobalABC (Alliance for Buildings and Construction), International Energy Agency, and UN Environment Programme. 2020. "GlobalABC Roadmap for Buildings and Construction: Towards a Zero-Emissions, Efficient, and Resilient Buildings and Construction Sector."

Global Climate Action. 2021. "Climate Action Pathway—Industry." Bonn, Germany: UN Framework Convention on Climate Change. https://unfccc.int/climate-action/marrakech-partnership/reporting-tracking/pathways/industry-climate-action-pathway.

Global Maritime Forum. 2022. "Mapping of Zero Emission Pilots and Demonstration Projects." Getting to Zero Coalition. https://www.globalmaritimeforum.org/publications/mapping-of-zero-emission-pilots-and-demonstration-projects.

Global Witness. 2021. "Last Line of Defence: The Industries Causing the Climate Crisis and Attacks against Land and Environmental Defenders." London: Global Witness. https://www.globalwitness.org/en/campaigns/environmental-activists/last-line-defence/.

Goldberg, L., D. Lagomasino, N. Thomas, and T. Fatoyinbo. 2020. "Global Declines in Human-Driven Mangrove Loss." *Global Change Biology* 26 (10): 5844–55. doi:10.1111/gcb.15275.

Goldman, E., M.J. Weisse, N. Harris, and M. Schneider. 2020. "Estimating the Role of Seven Commodities in Agriculture-Linked Deforestation: Oil Palm, Soy, Cattle, Wood Fiber, Cocoa, Coffee, and Rubber." Washington, DC: World Resources Institute. wri.org/publication/estimating-the-role-of-sevencommodities-in-agriculture-linked-deforestation.

Goldman School of Public Policy. 2021. *The 2035 Report*. Berkeley: University of California. https://www.2035report.com/transportation/.

Goldstein, A., W.R. Turner, S.A. Spawn, K.J. Anderson-Teixeira, S. Cook-Patton, J. Fargione, H.K. Gibbs, et al. 2020. "Protecting Irrecoverable Carbon in Earth's Ecosystems." *Nature Climate Change* 10 (4): 287–95. doi:10.1038/s41558-020-0738-8.

Government of China. 2009. *Carrying Out the Pilot Work of Demonstration and Promotion of Energy-Saving and New Energy Vehicles*. http://www.gov.cn/zwgk/2009-02/05/content_1222338.htm.

Graham-Rowe, E., S. Skippon, B. Gardner, and C. Abraham. 2011. "Can We Reduce Car Use and, If So, How? A Review of Available Evidence." *Transportation Research Part A: Policy and Practice* 45 (5): 401–18. doi:10.1016/j.tra.2011.02.001.

Grant, N., A. Hawkes, S. Mittal, and A. Gambhir. 2021. "Confronting Mitigation Deterrence in Low-Carbon Scenarios." *Environmental Research Letters* 16 (6): 064099. doi:10.1088/1748-9326/ac0749.

Gray, N., S. McDonagh, R. O'Shea, B. Smyth, and J.D. Murphy. 2021. "Decarbonising Ships, Planes and Trucks: An Analysis of Suitable Low-Carbon Fuels for the Maritime, Aviation and Haulage Sectors." *Advances in Applied Energy* 1 (February): 100008. doi:10.1016/j.adapen.2021.100008.

Green, C.P., J.S. Heywood, and M. Navarro Paniagua. 2020. "Did the London Congestion Charge Reduce Pollution?" *Regional Science and Urban Economics* 84 (September): 103573. doi:10.1016/j.regsciurbeco.2020.103573.

Greenhouse Gas Protocol. n.d. "Frequently Asked Questions." Calculation Tools. Accessed May 13, 2022. https://ghgprotocol.org/calculationg-tools-faq#:~:text=Direct%20GHG%20emissions%20are%20emissions,or%20controlled%20by%20another%20entity.

Gregersen, H., H. El Lakany, L. Bailey, and A. White. 2011. "Greener Side of REDD+: Lessons for REDD+ from Countries Where Forest Area Is Increasing." Washington, DC: Rights and Resources Initiative. http://rgdoi.net/10.13140/2.1.1410.6401.

Griffiths, S., B.K. Sovacool, J. Kim, M. Bazilian, and J.M. Uratani. 2021. "Industrial Decarbonization via Hydrogen: A Critical and Systematic Review of Developments, Socio-technical Systems and Policy Options." *Energy Research & Social Science* 80 (October): 102208. doi:10.1016/j.erss.2021.102208.

Griscom, B.W., J. Adams, P.W. Ellis, R.A. Houghton, G. Lomax, D.A. Miteva, W.H. Schlesinger, et al. 2017. "Natural Climate Solutions." *Proceedings of the National Academy of Sciences* 114 (44): 11645–50. doi:10.1073/pnas.1710465114.

Griscom, B.W., J. Busch, S.C. Cook-Patton, P.W. Ellis, J. Funk, S.M. Leavitt, G. Lomax, et al. 2020. "National Mitigation Potential from Natural Climate Solutions in the Tropics." *Philosophical Transactions of the Royal Society B: Biological Sciences* 375 (1794): 20190126. doi:10.1098/rstb.2019.0126.

Grubb, M., P. Drummond, and N. Hughes. 2021a. "The Shape and Pace of Change in the Transport Transition." London: UCL Institute for Sustainable Resources. https://www.wemeanbusinesscoalition.org/wp-content/uploads/2021/05/Shape-And-Pace-Of-Change-In-The-Transport-Transition-1.pdf.

Grubb, M., P. Drummond, J.-F. Mercure, C. Hepburn, P. Barbrook-Johnson, J. Carlos Ferraz, A. Clark, et al. 2021b. "The New Economics of Innovation and Transition: Evaluating Opportunities and Risks." Economics of Energy Innovation and System Transition Consortium (EEIST). https://eeist.co.uk/eeist-reports/.

Gruenwald, T., and M. Lee. 2020. "2020: Watt a Year for Building Electrification!" Rocky Mountain Institute. https://rmi.org/2020-watt-a-year-for-building-electrification/.

G7. 2021. "G7 Finance Ministers and Central Bank Governors' Communiqué." https://www.g7uk.org/g7-finance-ministers-and-central-bank-governors-communique/.

G7. 2022a. "G7 Climate, Energy and Environment Ministers' Communiqué." https://www.bundesregierung.de/resource/blob/974430/2044350/84e380088170c69e6b6ad45db-d133ef8/2022-05-27-1-climate-ministers-communique-data.pdf?download=1.

G7. 2022b. "G7 Leaders' Communiqué." Elmau, Germany: G7. https://www.g7germany.de/resource/blob/974430/2062292/9c213e6b4b36ed1bd687e82480040399/2022-07-14-leaders-communique-data.pdf?download=1.

Günther, A., A. Barthelmes, V. Huth, H. Joosten, G. Jurasinski, F. Koebsch, and J. Couwenberg. 2020. "Prompt Rewetting of Drained Peatlands Reduces Climate Warming despite Methane Emissions." *Nature Communications* 11 (1): 1644. doi:10.1038/s41467-020-15499-z.

Gürsan, C., and V. de Gooyert. 2021. "The Systemic Impact of a Transition Fuel: Does Natural Gas Help or Hinder the Energy Transition?" *Renewable and Sustainable Energy Reviews* 138 (March): 110552. doi:10.1016/j.rser.2020.110552.

Haberl, H., C. Mbow, X. Deng, E.G. Irwin, S. Kerr, T. Kuemmerle, O. Mertz, et al. 2014. "Finite Land Resources and Competition." In *Rethinking Global Land Use in an Urban Era*, edited by K.C. Seto and A. Reenberg, 35–69. Cambridge, MA: MIT Press. doi:10.7551/mitpress/9780262026901.003.0004.

Hall, S. 2021. "EC Wants Rules for Carbon Contracts for Difference: Draft." Montel Group, July 1. https://www.montelnews.com/news/1235264/ec-wants-rules-for-carbon-contracts-for-difference--draft.

Hall, D., and N. Lutsey. 2017. "Emerging Best Practices for Electric Vehicle Charging Infrastructure." San Francisco: International Council on Clean Transportation. https://theicct.org/publication/emerging-best-practices-for-electric-vehicle-charging-infrastructure/.

Hamilton, S.E., and D. Casey. 2016. "Creation of a High Spatio-temporal Resolution Global Database of Continuous Mangrove Forest Cover for the 21st Century (CGMFC-21)." *Global Ecology and Biogeography* 25 (6): 729–38. doi:10.1111/geb.12449.

Hampel, C. 2022. "War in Ukraine Halts Electric Car Supply Chains." *Electrek*, March 1. https://www.electrive.com/2022/03/01/war-in-ukraine-halts-electric-car-supply-chains/.

Hannon, E., J.T. Nijssen, S. Stern, and B. Sumers. 2020. "Transit Investments in an Age of Uncertainty." Frankfurt: McKinsey & Company. https://www.mckinsey.com/industries/public-and-social-sector/our-insights/transit-investments-in-an-age-of-uncertainty.

Hansen, M.C., P.V. Potapov, R. Moore, M. Hancher, S.A. Turubanova, A. Tyukavina, D. Thau, et al. 2013a. "High-Resolution Global Maps of 21st-Century Forest Cover Change." *Science* 342 (6160): 850–53. doi:10.1126/science.1244693.

Hanson, C., and J. Ranganathan. 2022. "How to Manage the Global Land Squeeze? Produce, Protect, Reduce, Restore." World Resources Institute (blog), February 14. https://www.wri.org/insights/manage-global-land-squeeze-produce-protect-reduce-restore.

Hanson, C., K. Buckingham, S. Dewitt, and L. Laestadius. 2015. "The Restoration Diagnostic: A Method for Developing Forest Landscape Restoration Strategies by Rapidly Assessing the Status of Key Success Factors." Washington, DC: World Resources Institute. https://www.wri.org/research/restoration-diagnostic.

Hare, B., G. Ganti, V. Maxwell, N. Das, A. Chapman, and M. Gidden. 2021. "Why Gas Is the New Coal." Berlin: Climate Analytics. https://climateanalytics.org/media/gas_is_new_coal_nov_2021_1_1.pdf.

Harris, N.L., D.A. Gibbs, A. Baccini, R.A. Birdsey, S. de Bruin, M. Farina, L. Fatoyinbo, et al. 2021. "Global Maps of Twenty-First Century Forest Carbon Fluxes." *Nature Climate Change* 11 (3): 234–40. doi:10.1038/s41558-020-00976-6.

Harvey, C. 2022. "Western 'Megadrought' Is the Worst in 1,200 Years." *Scientific American*, February 15. https://www.scientificamerican.com/article/western-megadrought-is-the-worst-in-1-200-years/.

Hasanbeigi, A., R. Becqué, and C. Springer. 2019. "Curbing Carbon from Consumption: The Role of Green Public Procurement." San Francisco: Global Efficiency Intelligence. https://www.climateworks.org/wp-content/uploads/2019/09/Green-Public-Procurement-Final-28Aug2019.pdf#:~:text=Curbing%20Carbon%20from%20Consumption%3A%20The%20Role%20of%20Green,can%20drive%20markets%20in%20the%20direction%20of%20sustainability.

Hasanbeigi, A., D. Shi, and H. Khutal. 2021. "Federal Buy Clean for Cement and Steel." San Francisco: Global Efficiency Intelligence. https://static1.squarespace.com/static/5877e86f9de4bb8bce72105c/t/614780a235d33358f77f09db/1632075952085/Federal+Buy+Clean+For+Cement+And+Steel-+Sept2021.pdf.

Hassan, I.A., H.S. Ramadan, M.A. Saleh, and D. Hissel. 2021. "Hydrogen Storage Technologies for Stationary and Mobile Applications: Review, Analysis and Perspectives." *Renewable and Sustainable Energy Reviews* 149 (October): 111311. doi:10.1016/j.rser.2021.111311.

Hearn, A.X., and R. Castaño-Rosa. 2021. "Towards a Just Energy Transition, Barriers and Opportunities for Positive Energy District Creation in Spain." *Sustainability* 13 (16): 8698. doi:10.3390/su13168698.

Hegarty, R.S., R.A. Passetti, K.M. Dittmer, Y. Wang, S. Shelton, J. Emmet-Booth, E. Wollenberg, et al. 2021. "An Evaluation of Emerging Feed Additives to Reduce Methane Emissions from Livestock." New Delhi: CGIAR Research Program on Climate Change, Agriculture and Food Security and New Zealand Agricultural Greenhouse Gas Research Centre initiative of the Global Research Alliance. https://cgspace.cgiar.org/handle/10568/116489.

Heilmayr, R., L.L. Rausch, J. Munger, and H.K. Gibbs. 2020. "Brazil's Amazon Soy Moratorium Reduced Deforestation." *Nature Food* 1 (12): 801–10. doi:10.1038/s43016-020-00194-5.

Hekkert, M.P., R.A.A. Suurs, S.O. Negro, S. Kuhlmann, and R.E.H.M. Smits. 2007. "Functions of Innovation Systems: A New Approach for Analysing Technological Change." *Technological Forecasting and Social Change* 74 (4): 413–32. doi:10.1016/j.techfore.2006.03.002.

Herr, D., M. von Unger, D. Laffoley, and A. McGivern. 2017. "Pathways for Implementation of Blue Carbon Initiatives." *Aquatic Conservation: Marine and Freshwater Ecosystems* 27 (September): 116–29. doi:10.1002/aqc.2793.

Hertwich, E., R. Lifset, S. Pauliuk, N. Heeren, S. Ali, Q. Tu, F. Ardente, et al. 2020. "Resource Efficiency and Climate Change—Material Efficiency Strategies for a Low-Carbon Future." Nairobi: UN Environment Programme. https://www.resourcepanel.org/file/1966/download?token=dNgPqfZE.

Hillemann, D., and T. Ehls. 2022. "FAQ: Germany Relies on Climate Protection Contracts (Carbon Contracts for Difference): What Do Companies Need to Know?" *Fieldfisher* (blog), December 1. https://www.fieldfisher.com/en/insights/faq-germany-relies-on-carbon-contracts-for-difference.

Hinge, A., and F. Brocklehurst. 2021. "Building Energy Codes and Other Mandatory Policies Applied to Existing Buildings." Richland, WA: Pacific Northwest National Laboratory, operated by the Battelle Memorial Institute for the U.S. Department of Energy. https://www.iea-ebc.org/Data/Sites/1/media/docs/working-groups/building-energy-codes/ebc_wg_becs_codesothermandatory-policies-existingbuildings_june_2021.pdf.

Hoang, N.T., and K. Kanemoto. 2021. "Mapping the Deforestation Footprint of Nations Reveals Growing Threat to Tropical Forests." *Nature Ecology & Evolution* 5 (6): 845–53. doi:10.1038/s41559-021-01417-z.

Höglund, R. 2022. "List of Known CDR Purchases | Marginal Carbon." https://docs.google.com/spreadsheets/d/1BH_B_Df_7e2l6AH8_8a0aK70nIAJXfCTwfyCgxkL5C8/edit?usp=embed_facebook.

Höhl, M., V. Ahimbisibwe, J.A. Stanturf, P. Elsasser, M. Kleine, and A. Bolte. 2020. "Forest Landscape Restoration: What Generates Failure and Success?" *Forests* 11 (9): 938. doi:10.3390/f11090938.

Hölscher, K., J.M. Wittmayer, and D. Loorbach. 2018. "Transition versus Transformation: What's the Difference?" *Environmental Innovation and Societal Transitions* 27 (June): 1–3. doi:10.1016/j.eist.2017.10.007.

Honegger, M., M. Poralla, A. Michaelowa, and H.-M. Ahonen. 2021. "Who Is Paying for Carbon Dioxide Removal? Designing Policy Instruments for Mobilizing Negative Emissions Technologies." *Frontiers in Climate* 3. https://www.frontiersin.org/article/10.3389/fclim.2021.672996.

Humpenöder, F., K. Karstens, H. Lotze-Campen, J. Leifeld, L. Menichetti, A. Barthelmes, and A. Popp. 2020. "Peatland Protection and Restoration Are Key for Climate Change Mitigation." *Environmental Research Letters* 15 (10): 104093. doi:10.1088/1748-9326/abae2a.

Hunt, J.D., E. Byers, Y. Wada, S. Parkinson, D.E.H.J. Gernaat, S. Langan, D.P. van Vuuren, and K. Riahi. 2020. "Global Resource Potential of Seasonal Pumped Hydropower Storage for Energy and Water Storage." *Nature Communications* 11 (1): 947. doi:10.1038/s41467-020-14555-y.

IATA (International Air Transport Association). 2021. "Net-Zero Carbon Emissions by 2050." October 4. https://www.iata.org/en/pressroom/2021-releases/2021-10-04-03/.

ICAT (Initiative for Climate Action Transparency). 2020. "Transformational Change Methodology: Assessing the Transformational Impacts of Policies and Actions." Copenhagen and Washington, DC: ICAT, UNEP DTU Partnership, World Resources Institute. https://climateactiontransparency.org/wp-content/uploads/2020/04/Transformational-Change-Assessment-Guide.pdf.

ICLEI (Local Governments for Sustainability). n.d. "Case Studies." Solutions Gateway. https://www.solutions-gateway.org/discover?area=cases.

IEA (International Energy Agency). 2017. "Energy Technology Perspectives 2017." Paris: IEA. www.iea.org/etp2017.

IEA. 2018. "Energy Service Companies (ESCOs): At the Heart of Innovative Financing Models for Efficiency." Paris: IEA. https://www.iea.org/reports/energy-service-companies-escos-2.

IEA. 2019a. *Global Status Report for Buildings and Construction, 2019*. Paris: IEA. https://www.iea.org/reports/global-status-report-for-buildings-and-construction-2019.

IEA. 2019b. "Perspectives for the Clean Energy Transition 2019: The Critical Role of Buildings." Paris: IEA. https://iea.blob.core.windows.net/assets/026bff1b-821d-48bc-8a0e-7c10280c62bc/Perspectives_for_the_Clean_Energy_Transition_2019.pdf.

IEA. 2020a. "Buildings Sector Energy Intensity in Selected Regions in the Sustainable Development Scenario, 2000–2030: Charts—Data & Statistics." Paris: IEA. https://www.iea.org/data-and-statistics/charts/buildings-sector-energy-intensity-in-selected-regions-in-the-sustainable-development-scenario-2000-2030.

IEA. 2020b. "Buildings Sector Energy-Related CO_2 Emissions in the Sustainable Development Scenario, 2000–2030: Charts—Data & Statistics." Paris: IEA. https://www.iea.org/data-and-statistics/charts/buildings-sector-energy-related-co2-emissions-in-the-sustainable-development-scenario-2000-2030.

IEA. 2020c. "CO_2 Emissions from Fuel Combustion Highlights: 2020." Paris: IEA. https://www.iea.org/data-and-statistics/data-product/co2-emissions-from-fuel-combustion-highlights.

IEA. 2020d. "Employment Multipliers for Investment in the Transport Sector." Paris: IEA. https://www.iea.org/data-and-statistics/charts/employment-multipliers-for-investment-in-the-transport-sector.

IEA. 2020e. "Energy Technology Perspectives 2020." Paris: IEA. https://www.iea.org/reports/energy-technology-perspectives-2020.

IEA. 2020f. "IEA Energy and Carbon Tracker 2020." Paris: IEA. https://www.iea.org/data-and-statistics/data-product/iea-energy-and-carbon-tracker-2020.

IEA. 2020g. "Sustainable Recovery." Paris: IEA. https://www.iea.org/reports/sustainable-recovery.

IEA. 2020h. "Tracking Buildings 2020." Paris: IEA. 2020. https://www.iea.org/reports/tracking-buildings-2020.

IEA. 2020i. "Tracking Buildings 2020: Building Envelopes." Paris: IEA. 2020. https://www.iea.org/reports/tracking-buildings-2020.

IEA. 2020j. "Tracking Buildings 2020: Cooling." Paris: IEA. 2020. https://www.iea.org/reports/cooling.

IEA. 2020k. "Tracking Buildings 2020: Heat Pumps." Paris: IEA. 2020. https://www.iea.org/reports/tracking-buildings-2020.

IEA. 2021a. "Aviation." Paris: IEA. https://www.iea.org/reports/aviation.

IEA. 2021b. "Electric Vehicles Tracking Report." Paris: IEA. https://www.iea.org/reports/electric-vehicles.

IEA. 2021c. "Financing Clean Energy Transitions in Emerging and Developing Economies." Paris: IEA. https://www.iea.org/reports/financing-clean-energy-transitions-in-emerging-and-developing-economies.

IEA. 2021d. "Global Energy Review 2021." Paris: IEA. https://www.iea.org/reports/global-energy-review-2021.

IEA. 2021e. "Global Hydrogen Review 2021." Paris: IEA. https://www.iea.org/reports/global-hydrogen-review-2021.

IEA. 2021f. "Greenhouse Gas Emissions from Energy 2021." Paris: IEA. https://www.iea.org/data-and-statistics/data-product/greenhouse-gas-emissions-from-energy.

IEA. 2021g. "International Shipping." Paris: IEA. https://www.iea.org/reports/international-shipping.

IEA. 2021h. "Net Zero by 2050: A Roadmap for the Global Energy Sector." Paris: IEA. https://www.iea.org/reports/net-zero-by-2050.

IEA. 2021i. "Net Zero by 2050 Hinges on a Global Push to Increase Energy Efficiency." Paris: IEA. https://www.iea.org/articles/net-zero-by-2050-hinges-on-a-global-push-to-increase-energy-efficiency.

IEA. 2021j. "Tracking Buildings." Paris: IEA. https://www.iea.org/reports/tracking-buildings-2021.

IEA. 2021k. "Tracking Buildings 2021: Cooling." Paris: IEA. https://www.iea.org/reports/cooling.

IEA. 2021l. "Tracking Buildings 2021: Heat Pumps." Paris: IEA. https://www.iea.org/reports/heat-pumps.

IEA. 2021m. "Tracking Buildings 2021: Heating." Paris: IEA. https://www.iea.org/reports/heating.

IEA. 2021n. "Tracking Power 2021." Paris: IEA. https://www.iea.org/reports/tracking-power-2021.

IEA. 2021o. "Trends and Developments in Electric Vehicle Markets." Global EV Outlook 2021. Paris: IEA. https://www.iea.org/reports/global-ev-outlook-2021/trends-and-developments-in-electric-vehicle-markets#abstract.

IEA. 2021p. "Trucks and Buses: Tracking Progress 2021." Paris: IEA. https://www.iea.org/reports/trucks-and-buses.

IEA. 2021q. "World Energy Balances: Energy Balances for 190 Countries and Regional Aggregates." Paris: IEA. https://www.iea.org/data-and-statistics/data-product/world-energy-balances.

IEA. 2021r. "World Energy Balances 2021." Paris: IEA.

IEA. 2021s. "World Energy Investment 2021." Paris: IEA. https://www.iea.org/reports/world-energy-investment-2021.

IEA. 2021t. "How Energy Efficiency Will Power Net Zero Climate Goals." March 29. Paris: IEA. https://www.iea.org/commentaries/how-energy-efficiency-will-power-net-zero-climate-goals.

IEA. 2022a. "Direct Air Capture: A Key Technology for Net Zero." Paris: IEA. https://iea.blob.core.windows.net/assets/78633715-15c0-44e1-81df-41123c556d57/DirectAirCapture_Akeytechnologyfornetzero.pdf.

IEA. 2022b. "Global Electric Vehicle Outlook 2022." Paris: IEA. https://iea.blob.core.windows.net/assets/ad8fb04c-4f75-42fc-973a-6e54c8a4449a/GlobalElectricVehicleOutlook2022.pdf.

IEA. 2022c. "Global Energy Review: CO_2 Emissions in 2021." Paris: IEA. https://www.iea.org/reports/global-energy-review-co2-emissions-in-2021-2.

IEA. 2022d. "Hydrogen Projects Database." Paris: IEA. https://www.iea.org/data-and-statistics/data-product/hydrogen-projects-database.

IEA. 2022e. "Tracking the Impact of Fossil-Fuel Subsidies." Paris: IEA. https://www.iea.org/topics/energy-subsidies.

IEA. 2022f. "Global Supply Chains of EV Batteries." Paris: IEA. https://www.iea.org/reports/global-supply-chains-of-ev-batteries.

IEA/4E TCP. 2021. "Achievements of Energy Efficiency Appliance and Equipment Standards and Labelling Programmes." Paris: IEA. https://www.iea.org/reports/achievements-of-energy-efficiency-appliance-and-equipment-standards-and-labelling-programmes.

IEEFA (Institute for Energy Economics and Financial Analysis). 2020. "New Regulations Threaten Vietnam's Remaining Coal Pipeline." https://ieefa.org/wp-content/uploads/2020/10/New-Regulations-Threaten-Vietnams-Remaining-Coal-Pipeline_November-2020.pdf.

IFPRI (International Food Policy Research Institute). 2022. *Global Food Policy Report*: *Climate Change and Food Systems*. doi:10.2499/9780896294257.

IGAD (Intergovernmental Authority on Development). 2022. *2022 Global Report on Food Crises*: *Regional Focus on the Intergovernmental Authority on Development Member States*. Djibouti: IGAD. https://www.icpac.net/documents/572/IGAD_RRFC_2022_ONLINE_4eYMbKh.pdf.

IIF (Institute of International Finance). 2021. "Taskforce on Scaling Voluntary Carbon Markets." Washington, DC: IIF. https://www.iif.com/Portals/1/Files/TSVCM_Report.pdf.

IISD (International Institute for Sustainable Development). 2022. "Energy Policy Tracker." https://www.energypolicytracker.org/.

IMF (International Monetary Fund). 2019. "Fiscal Policies for Paris Climate Strategies: From Principle to Practice." Washington, DC: IMF. http://elibrary.imf.org/view/IMF007/25996-9781498311717/25996-9781498311717/25996-9781498311717.xml.

IMF. 2021a. "Fossil Fuel Subsidies." Washington, DC: IMF. https://www.imf.org/en/Topics/climate-change/energy-subsidies.

IMF. 2021b. "IMF Strategy to Help Members Address Climate Change Related Policy Challenges—Priorities, Modes of Delivery, and Budget Implications." Washington, DC: IMF. https://www.imf.org/en/Publications/Policy-Papers/Issues/2021/07/30/IMF-Strategy-to-Help-Members-Address-Climate-Change-Related-Policy-Challenges-Priorities-463093.

IMO (International Maritime Organization). 2020. "Fourth IMO Greenhouse Gas Study." London: IMO.

Indrajaya, Y., T.W. Yuwati, S. Lestari, B. Winarno, B.H. Narendra, H.Y.S.H. Nugroho, D. Rachmanadi, et al. 2022. "Tropical Forest Landscape Restoration in Indonesia: A Review." *Land* 11 (3): 328. doi:10.3390/land11030328.

InfluenceMap. 2020. "Fossil Fuel Lobbyists Are Dominating Climate Policy Battles during COVID-19." London: InfluenceMap. https://influencemap.org/report/Fossil-Fuel-Lobbyists-Are-Dominating-Climate-Policy-Battles-During-COVID-19-a78b11aa1be42aef5d7078d09457603b.

InfluenceMap. 2022. "The Automotive Sector and Climate Change." London: InfluenceMap. https://influencemap.org/report/The-Automotive-Sector-and-Climate-Change-18218.

IPBES (Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services). 2019. *Global Assessment Report on Biodiversity and Ecosystem Services.* Edited by E.S. Brondizio, J. Settele, and S. Díaz. Bonn, Germany: IPBES Secretariat. https://doi.org/10.5281/zenodo.3831673.

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

IPCC. 2019a. *Climate Change and Land: An IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems*. Edited by P.R. Shukla, J. Skea, E.C. Buendia, V. Masson-Delmotte, H.-O. Pörtner, D.C. Roberts, P. Zhai, et al. Cambridge: Cambridge University Press. https://www.ipcc.ch/srccl/.

IPCC. 2021. *Climate Change 2021: The Physical Science Basis—Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Edited by V. Masson-Delmotte, P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, et al. Cambridge: Cambridge University Press. https://www.ipcc.ch/report/ar6/wg1/.

IPCC. 2022a. *Climate Change 2022: Impacts, Adaptation, and Vulnerability—Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Edited by H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, et al. Cambridge: Cambridge University Press. https://www.ipcc.ch/report/sixth-assessment-report-working-group-ii/.

IPCC. 2022b. *Climate Change 2022: Mitigation of Climate Change—Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.* Edited by P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, et al. Cambridge: Cambridge University Press. https://www.ipcc.ch/report/ar6/wg3/.

IRENA (International Renewable Energy Agency). 2018. "Global Energy Transformation: A Roadmap to 2050." Abu Dhabi: IRENA. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2018/Apr/IRENA_Report_GET_2018.pdf.

IRENA. 2019. "Advanced Biofuels: What Holds Them Back?" Abu Dhabi: IRENA. https://irena.org/publications/2019/Nov/Advanced-biofuels-What-holds-them-back.

IRENA. 2021a. "Renewable Capacity Highlights." Abu Dhabi: IRENA.

IRENA. 2021b. "Renewable Power Generation Costs in 2020." Abu Dhabi: IRENA. https://www.irena.org/publications/2021/Jun/Renewable-Power-Costs-in-2020.

IRENA. 2022a. "Renewable Capacity Statistics 2022." Abu Dhabi: IRENA. https://www.irena.org/publications/2022/Apr/Renewable-Capacity-Statistics-2022.

IRENA. 2022b. "Renewable Power Generation Costs in 2021." Abu Dhabi: IRENA. https://www.irena.org/publications/2022/Jul/Renewable-Power-Generation-Costs-in-2021.

IRENA. 2022c. "NDCs and Renewable Energy Targets in 2021: Are We on the Right Path to a Climate-Safe Future?" January. https://www.irena.org/publications/2022/Jan/NDCs-and-Renewable-Energy-Targets-in-2021.

Irfan, U. 2018. "Exxon Is Lobbying for a Carbon Tax: There Is, Obviously, a Catch." *Vox*, October 18. https://www.vox.com/2018/10/18/17983866/climate-change-exxon-carbon-tax-lawsuit.

ITDP (Institute for Transportation and Development Policy). 2018. "China Tackles Climate Change with Electric Buses." ITDP (blog), September 11. https://www.itdp.org/2018/09/11/electric-buses-china/.

ITDP. 2021. "Rapid Transit Database." https://www.itdp.org/rapid-transit-database/.

ITDP. 2022. "Making the Economic Case for Cycling." New York: ITDP. https://www.itdp.org/publication/economics-of-cycling.

ITF (International Transport Forum). 2020. "Good to Go? Assessing the Environmental Performance of New Mobility." Paris: ITF. https://www.itf-oecd.org/good-to-go-environmental-performance-new-mobility.

ITF. 2021. "ITF Transport Outlook 2021." Paris: ITF. https://www.oecd-ilibrary.org/transport/itf-transport-outlook-2021_16826a30-en.

IUCN (International Union for Conservation of Nature). 2020. "Restore Our Future: Impact and Potential of Forest Landscape Restoration." Bonn, Germany: IUCN. https://www.bonnchallenge.org/resources/bonn-challenge-2020-report.

Jack, B.K. 2013. "Market Inefficiencies and the Adoption of Agricultural Technologies in Developing Countries." Agricultural Technology Adoption Initiative, Abdul Latif Jameel Poverty Action Lab (Massachusetts Institute of Technology); and Center for Effective Global Action (University of California, Berkeley). https://escholarship.org/content/qt6m25r19c/qt6m25r19c_noSplash_036bc34d0037409bf59acb8a699577ff.pdf?t=oa7jim.

Jaeger, J. 2021. “Explaining the Exponential Growth of Renewable Energy.” *Insights* (blog), September 20. Washington, DC: World Resources Institute. https://www.wri.org/insights/growth-renewable-energy-sector-explained.

Jaeger, J., G. Walls, E. Clarke, J.C. Altamirano, A. Harsono, H. Mountford, S. Burrow, et al. 2021. “The Green Jobs Advantage: How Climate-Friendly Investments Are Better Job Creators.” Washington, DC: World Resources Institute. https://www.wri.org/research/green-jobs-advantage-how-climate-friendly-investments-are-better-job-creators.

Jakovac, C.C., A.E. Latawiec, E. Lacerda, I. Leite Lucas, K.A. Korys, A. Iribarrem, G.A. Malaguti, et al. 2020. “Costs and Carbon Benefits of Mangrove Conservation and Restoration: A Global Analysis.” *Ecological Economics* 176 (October): 106758. doi:10.1016/j.ecolecon.2020.106758.

Jolley, G.J., C. Khalaf, G. Michaud, and A.M. Sandler. 2018. “The Economic, Fiscal, and Workforce Impacts of Coal-Fired Power Plant Closures in Appalachian Ohio.” September 18. https://geog.umd.edu/sites/geog.umd.edu/files/pubs/The%20economic%20fiscal%20and%20workforce%20impacts%20of%20coal%20fired%20powerplant%20closures%20in%20Appalachian%20Ohio%20Jolley%20Khalaf%20Michaud%20Sandler%202019%20Regional%20Science%20Policy%20and%20Practice.pdf.

Jolly, W.M., M.A. Cochrane, P.H. Freeborn, Z.A. Holden, T.J. Brown, G.J. Williamson, and D.M.J.S. Bowman. 2015. “Climate-Induced Variations in Global Wildfire Danger from 1979 to 2013.” *Nature Communications* 6 (1): 7537. doi:10.1038/ncomms8537.

Joosten, H. 2021. “Global Guidelines for Peatland Rewetting and Restoration.” Ramsar Technical Report no. 11. Gland, Switzerland: Secretariat of the Convention on Wetlands. https://www.researchgate.net/publication/359773792_Global_guidelines_for_peatland_rewetting_and_restoration.

Kaufmann, D., and A. Kraay. 2007. “Governance Indicators: Where Are We, Where Should We Be Going?” Washington, DC: World Bank. http://info.worldbank.org/governance/wgi/pdf/wps4370.pdf.

Kaufmann, D., and A. Kraay. 2020. “Worldwide Governance Indicators.” Washington, DC: World Bank. http://info.worldbank.org/governance/wgi/.

Kearns, J., G. Teletzke, J. Palmer, H. Thomann, H. Kheshgi, Y.-H.H. Chen, S. Paltsev, and H. Herzog. 2017. “Developing a Consistent Database for Regional Geologic CO_2 Storage Capacity Worldwide.” *Energy Procedia* 114 (July): 4697–709. doi:10.1016/j.egypro.2017.03.1603.

Kersey, J., N.D. Popovich, and A.A. Phadke. 2022. “Rapid Battery Cost Declines Accelerate the Prospects of All-Electric Interregional Container Shipping.” *Nature Energy* 7 (7): 664–74. doi:10.1038/s41560-022-01065-y.

Khan, M.F.A., and L. Giessen. 2021. “Exceptional Bureaucratic Rivalry in Mangrove Forest Policy: Explanations from the Sundarbans, Bangladesh.” *Ocean & Coastal Management* 203 (April): 105510. doi:10.1016/j.ocecoaman.2020.105510.

Kim, S., S. Lee, E. Ko, K. Jang, and J. Yeo. 2021. “Changes in Car and Bus Usage amid the COVID-19 Pandemic: Relationship with Land Use and Land Price.” *Journal of Transport Geography* 96 (October): 103168. doi:10.1016/j.jtrangeo.2021.103168.

Klenert, D., L. Mattauch, E. Combet, O. Edenhofer, C. Hepburn, R. Rafaty, and N. Stern. 2018. “Making Carbon Pricing Work for Citizens.” *Nature Climate Change* 8 (8): 669–77. doi:10.1038/s41558-018-0201-2.

Klock-McCook, E.J., S. Li, R. McLane, D. Mullaney, and J. Schroder. 2021. “EV Charging for All.” New York: Rocky Mountain Institute. https://rmi.org/insight/ev-charging-for-all/.

Koks, E., R. Pant, S. Thacker, and J.W. Hall. 2019. “Understanding Business Disruption and Economic Losses Due to Electricity Failures and Flooding.” *International Journal of Disaster Risk Science* 10 (4): 421–38. doi:10.1007/s13753-019-00236-y.

Komendantova, N., and A. Battaglini. 2016. “Social Challenges of Electricity Transmission: Grid Deployment in Germany, the United Kingdom, and Belgium.” *IEEE Power and Energy Magazine* 14 (4): 79–87. doi:10.1109/MPE.2016.2550399.

Koohi-Fayegh, S., and M.A. Rosen. 2020. “A Review of Energy Storage Types, Applications and Recent Developments.” *Journal of Energy Storage* 27 (February): 101047. doi:10.1016/j.est.2019.101047.

Kosar, U., V. Suarez, G. Amador, M. Glicksman, C. Holness, R. Jacobson, L.D. Simonelli, and T. Steeves. 2021. “Removing Forward: Centering Equity and Justice in a Carbon Removing Future.” Washington, DC: Carbon 180. https://static1.squarespace.com/static/5b9362d89d5abb8c51d474f8/t/6115485ae47e7f00829083e1/1628784739915/Carbon180+RemovingForward.pdf.

Kouassi, J.-L., A. Kouassi, Y. Bene, D. Konan, E.J. Tondoh, and C. Kouame. 2021. “Exploring Barriers to Agroforestry Adoption by Cocoa Farmers in South-Western Côte d’Ivoire.” *Sustainability* 13 (23): 13075. doi:10.3390/su132313075.

Kreyling, J., F. Tanneberger, F. Jansen, S. van der Linden, C. Aggenbach, V. Blüml, J. Couwenberg, et al. 2021. “Rewetting Does Not Return Drained Fen Peatlands to Their Old Selves.” *Nature Communications* 12 (1): 5693. doi:10.1038/s41467-021-25619-y.

Kröner, N., and A. Newman. 2021. “The TCFD Framework Has Pushed Climate-Related Financial Reporting into the Mainstream.” *South Pole* (blog), April 12. https://www.southpole.com/blog/the-tcfd-framework-has-pushed-climate-related-financial-reporting-into-the-mainstream---companies-must-move-fast.

Krupnick, A. 2020. “Green Public Procurement for Natural Gas, Cement, and Steel.” Washington, DC: Resources of the Future. https://media.rff.org/documents/RFF_WP_20-17_Green_Public_Procurement_for_Natural_Gas_Cement_and_Steel.pdf.

Kucharavy, D., and R. De Guio. 2011. “Logistic Substitution Model and Technological Forecasting.” *Procedia Engineering*, Proceeding of the ETRIA World TRIZ Future Conference, 9 (January): 402–16. doi:10.1016/j.proeng.2011.03.129.

Kuramochi, T., N. Höhne, M. Schaeffer, J. Cantzler, B. Hare, Y. Deng, S. Sterl, et al. 2018. “Ten Key Short-Term Sectoral Benchmarks to Limit Warming to 1.5°C.” *Climate Policy* 18 (3): 287–305. doi:10.1080/14693062.2017.1397495.

Kuss, P., and K.A. Nicholas. 2022. "A Dozen Effective Interventions to Reduce Car Use in European Cities: Lessons Learned from a Meta-analysis and Transition Management." *Case Studies on Transport Policy*, February, S2213624X22000281. doi:10.1016/j.cstp.2022.02.001.

Lackner, K.S., and H. Azarabadi. 2021. "Buying Down the Cost of Direct Air Capture." *Industrial & Engineering Chemistry Research* 60 (22): 8196–208. doi:10.1021/acs.iecr.0c04839.

Lamb, W.F., T. Wiedmann, J. Pongratz, R. Andrew, M. Crippa, J.G.J. Olivier, D. Wiedenhofer, et al. 2021. "A Review of Trends and Drivers of Greenhouse Gas Emissions by Sector from 1990 to 2018." *Environmental Research Letters* 16 (7): 073005. doi:10.1088/1748-9326/abee4e.

Lambin, E.F., H.K. Gibbs, R. Heilmayr, K.M. Carlson, L.C. Fleck, R.D. Garrett, Y. Le Polain de Waroux, et al. 2018. "The Role of Supply-Chain Initiatives in Reducing Deforestation." *Nature Climate Change* 8 (2): 109–16. doi:10.1038/s41558-017-0061-1.

LandMark Map. 2021. "Global Platform of Indigenous and Community Lands." https://www.landmarkmap.org/.

Lane, C. 2022. "Effects of Women's Empowerment Interventions in Food Systems." Nairobi: International Livestock Research Institute. https://gender.cgiar.org/news/effects-womens-empowerment-interventions-food-systems.

Larsen, J., W. Herndon, and G. Hiltbrand. 2020. "Capturing New Jobs: The Employment Opportunities Associated with Scale-up of Direct Air Capture (DAC) Technology in the US." New York: Rhodium Group. https://rhg.com/wp-content/uploads/2020/06/Capturing-New-Jobs-Employment-Opportunities-from-DAC-Scale-Up.pdf.

Larson, E., C. Greig, and J. Jenkins. 2021. "Net-Zero America Project: Rapid Switch—Andlinger Center." Princeton, NJ: Princeton University. https://acee.princeton.edu/rapidswitch/projects/net-zero-america-project/.

Lawrence, D., M. Coe, W. Walker, L. Verchot, and K. Vandecar. 2022. "The Unseen Effects of Deforestation: Biophysical Effects on Climate." *Frontiers in Forests and Global Change* 5 (March): 756115. doi:10.3389/ffgc.2022.756115.

Lazos-Chavero, E., J. Zinda, A. Bennett-Curry, P. Balvanera, G. Bloomfield, C. Lindell, and C. Negra. 2016. "Stakeholders and Tropical Reforestation: Challenges, Trade-Offs, and Strategies in Dynamic Environments." *Biotropica* 48 (6): 900–914. doi:10.1111/btp.12391.

Leadit. 2021. "Green Steel Tracker." November. https://www.industrytransition.org/green-steel-tracker/.

Lebedys, A., D. Akande, N. Coënt, N. Elhassan, G. Escamilla, I. Arkhipova, and A. Whiteman. 2022. "Renewable Capacity Statistics 2022." Abu Dhabi: IRENA. https://irena.org/-/media/Files/IRENA/Agency/Publication/2022/Apr/IRENA_RE_Capacity_Statistics_2022.pdf.

Lebling, K., M. Ge, K. Levin, R. Waite, J. Friedrich, C. Elliott, K. Ross, et al. 2020. "State of Climate Action: Assessing Progress toward 2030 and 2050." Washington, DC: World Resources Institute. https://www.wri.org/research/state-climate-action-assessing-progress-toward-2030-and-2050.

Lebling, K., H. Leslie-Bole, P. Psarras, E. Bridgwater, Z. Byrum, and H. Pilorgé. 2022. "Direct Air Capture: Assessing Impacts to Enable Responsible Scaling." April. Washington, DC: World Resources Institute. https://www.wri.org/research/direct-air-capture-impacts.

Lechtenböhmer, S., L.J. Nilsson, M. Åhman, and C. Schneider. 2016. "Decarbonising the Energy Intensive Basic Materials Industry through Electrification: Implications for Future EU Electricity Demand." *Energy* 115 (November): 1623–31. doi:10.1016/j.energy.2016.07.110.

Lee, S.Y., S. Hamilton, E.B. Barbier, J. Primavera, and R.R. Lewis. 2019. "Better Restoration Policies Are Needed to Conserve Mangrove Ecosystems." *Nature Ecology & Evolution* 3 (6): 870–72. doi:10.1038/s41559-019-0861-y.

Legesse, B.A., K. Jefferson-Moore, and T. Thomas. 2018. "Impacts of Land Tenure and Property Rights on Reforestation Intervention in Ethiopia." *Land Use Policy* 70 (January): 494–99. doi:10.1016/j.landusepol.2017.11.018.

Leifeld, J., and L. Menichetti. 2018. "The Underappreciated Potential of Peatlands in Global Climate Change Mitigation Strategies." *Nature Communications* 9 (1): 1071. doi:10.1038/s41467-018-03406-6.

Leifeld, Jens, C. Wüst-Galley, and S. Page. 2019. "Intact and Managed Peatland Soils as a Source and Sink of GHGs from 1850 to 2100." *Nature Climate Change* 9 (12): 945–47. doi:10.1038/s41558-019-0615-5.

Lenton, T.M. 2020. "Tipping Positive Change." *Philosophical Transactions of the Royal Society B: Biological Sciences* 375 (1794): 20190123. doi:10.1098/rstb.2019.0123.

Lenton, T.M., H. Held, E. Kriegler, J.W. Hall, W. Lucht, S. Rahmstorf, and H.J. Schellnhuber. 2008. "Tipping Elements in the Earth's Climate System." *Proceedings of the National Academy of Sciences* 105 (6): 1786–93. doi:10.1073/pnas.0705414105.

Leo, K.L., C.L. Gillies, J.A. Fitzsimons, L.Z. Hale, and M.W. Beck. 2019. "Coastal Habitat Squeeze: A Review of Adaptation Solutions for Saltmarsh, Mangrove and Beach Habitats." *Ocean & Coastal Management* 175 (June): 180–90. doi:10.1016/j.ocecoaman.2019.03.019.

Levin, K., B. Cashore, S. Bernstein, and G. Auld. 2012. "Overcoming the Tragedy of Super Wicked Problems: Constraining Our Future Selves to Ameliorate Global Climate Change." *Policy Sciences* 45 (2): 123–52. doi:10.1007/s11077-012-9151-0.

Levin, K., S. Boehm, N. Singh, A. Maassen, M. Galvin, F. McRaith, R. Becqué, J. Brand, C. Elliott, and S. Shaz. 2020. "Safeguarding Our Global Commons: A Systems Change Lab to Monitor, Learn from, and Advance Transformational Change." Washington, DC: World Resources Institute. https://globalcommonsalliance.org/wp-content/uploads/2020/12/Systems-Change-Paper.pdf.

Lewis, M. 2020. "Renewables Bring Deflation to the Energy Sector." *Financial Times*, December 16. https://www.ft.com/content/f2a27ddb-ea88-46cc-a265-ef84bd50946b.

Lewis, R.R. 2001. "Mangrove Restoration: Costs and Benefits of Successful Ecological Restoration." In *Proceedings of the Mangrove Valuation Workshop, Universiti Sains Malaysia, Penang*. https://www.fao.org/forestry/10560-0fe87b898806287615fce-b95a76f613cf.pdf.

Lex. 2021. "COP26: Carney's $130tn Climate Pledge Is Too Big to Be Credible." *Financial Times*, November 3. https://www.ft.com/content/87690ee9-c9b1-44b6-881b-368139560295.

Li, J., and C. Sun. 2018. "Towards a Low Carbon Economy by Removing Fossil Fuel Subsidies?" *China Economic Review* 50 (August): 17–33. doi:10.1016/j.chieco.2018.03.006.

Lim, C.L., G.W. Prescott, J.D.T. De Alban, A.D. Ziegler, and E.L. Webb. 2017. "Untangling the Proximate Causes and Underlying Drivers of Deforestation and Forest Degradation in Myanmar." *Conservation Biology* 31 (6): 1362–72. doi:10.1111/cobi.12984.

Lipinski, B. 2020. "SDG Target 12.3 on Food Loss and Waste: 2020 Progress Report | Champions 12.3." Washington, DC: World Resources Institute. https://champions123.org/publication/sdg-target-123-food-loss-and-waste-2020-progress-report.

Litman, T. 2022. "Are Vehicle Travel Reduction Targets Justified?" Victoria Transport Policy Institute. http://www.vtpi.org/vmt_red.pdf.

Liu, J., Q. Yang, Y. Zhang, W. Sun, and Y. Xu. 2019. "Analysis of CO_2 Emissions in China's Manufacturing Industry Based on Extended Logarithmic Mean Division Index Decomposition." *Sustainability* 11 (1): 226. doi:10.3390/su11010226.

Liu, G., Y. Tan, and X. Li. 2020. "China's Policies of Building Green Retrofit: A State-of-the-Art Overview." *Building and Environment* 169: 106554. doi:https://doi.org/10.1016/j.buildenv.2019.106554.

Lo, J. 2022. "UK Freezes International Aid to Keep within Self-Imposed Limit." *Climate Home News*, July 25. https://www.climatechangenews.com/2022/07/25/uk-freezes-international-aid-to-keep-within-self-imposed-limit/.

Lockwood, M. 2021. "A Hard Act to Follow? The Evolution and Performance of UK Climate Governance." *Environmental Politics* 30 (sup1): 26–48. doi:10.1080/09644016.2021.1910434.

Löfqvist, S., and J. Ghazoul. 2019. "Private Funding Is Essential to Leverage Forest and Landscape Restoration at Global Scales." *Nature Ecology & Evolution* 3 (12): 1612–15. doi:10.1038/s41559-019-1031-y.

Lovejoy, T.E., and C. Nobre. 2019. "Amazon Tipping Point: Last Chance for Action." *Science Advances* 5 (12): eaba2949. doi:10.1126/sciadv.aba2949.

Lovelock, C.E., and B.M. Brown. 2019. "Land Tenure Considerations Are Key to Successful Mangrove Restoration." *Nature Ecology & Evolution* 3 (8): 1135–1135. doi:10.1038/s41559-019-0942-y.

Lucas, H., S. Pinnington, and L.F. Cabeza. 2018. "Education and Training Gaps in the Renewable Energy Sector." *Solar Energy* 173 (October): 449–55. doi:10.1016/j.solener.2018.07.061.

Lütkehermöller, K., V. Hector, and A. Kachi. 2021. "Climate, COVID-19, and the Developing Country Debt Crisis." Cologne, Germany: NewClimate Institute. https://newclimate.org/resources/publications/climate-covid-19-and-the-developing-country-debt-crisis.

Lyons, K. 2018. "How Scientists Used Lasers, Satellites and Planes to Map One of Indonesia's Biggest Sources of Emissions." *Insights* (blog), October 1. Washington, DC: World Resources Institute. https://www.wri.org/insights/how-scientists-used-lasers-satellites-and-planes-map-one-indonesias-biggest-sources.

Lyons, M., P. Durrant, and K. Kochhar. 2021. "Reaching Zero with Renewables: Capturing Carbon." Abu Dhabi: IRENA. https://irena.org/-/media/Files/IRENA/Agency/Technical-Papers/IRENA_Capturing_Carbon_2021.pdf.

Mace, M.J., C.L. Fyson, M. Schaeffer, and W.L. Hare. 2018. "Governing Large-Scale Carbon Dioxide Removal: Are We Ready?" New York: Carnegie Climate Geoengineering Governance Initiative (C2G2). https://www.c2g2.net/wp-content/uploads/C2G2-2018-CDR-Governance-1.pdf.

Mackey, B., C.F. Kormos, H. Keith, W.R. Moomaw, R.A. Houghton, R.A. Mittermeier, D. Hole, and S. Hugh. 2020. "Understanding the Importance of Primary Tropical Forest Protection as a Mitigation Strategy." *Mitigation and Adaptation Strategies for Global Change* 25 (5): 763–87. doi:10.1007/s11027-019-09891-4.

Macquarie, R., B. Nara, P. Rosane, M. Solomon, C. Wetherbee, and B. Buchner. 2020. "Updated View on the Global Landscape of Climate Finance 2019." London: Climate Policy Initiative. https://www.climatepolicyinitiative.org/publication/updated-view-on-the-global-landscape-of-climate-finance-2019/.

Macreadie, P.I., A. Anton, J.A. Raven, N. Beaumont, R.M. Connolly, D.A. Friess, J.J. Kelleway, et al. 2019. "The Future of Blue Carbon Science." *Nature Communications* 10 (1): 3998. doi:10.1038/s41467-019-11693-w.

Mahendra, A., R. King, J. Du, A. Dasgupta, V.A. Beard, A. Kallergis, and K. Schalch. 2021. *Seven Transformations for More Equitable and Sustainable Cities*. World Resources Report. Washington, DC: World Resources Institute. https://publications.wri.org/transformations-equitable-sustainable-cities.

Malinauskaite, J., H. Jouhara, L. Ahmad, M. Milani, L. Montorsi, and M. Venturelli. 2019. "Energy Efficiency in Industry: EU and National Policies in Italy and the UK." *Energy* 172 (April): 255–69. doi:10.1016/j.energy.2019.01.130.

Malins, C. 2017. "What Role Is There for Electrofuel Technologies in European Transport's Low Carbon Future?" London: Cerulogy. https://www.transportenvironment.org/wp-content/uploads/2021/07/2017_11_Cerulogy_study_What_role_electrofuels_final_0.pdf.

Mallouppas, G., and E. Yfantis. 2021. "Decarbonization in Shipping Industry: A Review of Research, Technology Development, and Innovation Proposals." *Journal of Marine Science and Engineering* 9 (4): 415. doi:10.3390/jmse9040415.

Markusson, N., D. McLaren, and D. Tyfield. 2018. "Towards a Cultural Political Economy of Mitigation Deterrence by Negative Emissions Technologies (NETs)." *Global Sustainability* 1. doi:10.1017/sus.2018.10.

Marrakech Partnership and Global Climate Action. 2021. "Climate Action Pathway: Human Settlements." https://unfccc.int/climate-action/marrakech-partnership/reporting-tracking/pathways/human-settlements-climate-action-pathway.

Marshall, G., D. Conway, R. Webster, L. Comeau, D.J. Besley, and I. Saldarriaga Arango. 2018. "Guide to Communicating Carbon Pricing." Washington, DC: World Bank Group. https://documents.worldbank.org/en/publication/documents-reports/documentdetail/668481543351717355/guide-to-communicating-carbon-pricing.

Mayer, A. 2018. "A Just Transition for Coal Miners? Community Identity and Support from Local Policy Actors." *Environmental Innovation and Societal Transitions* 28 (September): 1–13. doi:10.1016/j.eist.2018.03.006.

Mazza, F., J. Falzon, and B. Buchner. 2016. "Global Climate Finance: An Updated View on 2013 and 2014 Flows." London: Climate Policy Initiative. https://www.climatepolicyinitiative.org/publication/global-climate-finance-updated-view-2013-2014-flows/.

McCormick, C. 2022. "Who Pays for DAC? The Market and Policy Landscape for Advancing Direct Air Capture." National Academy of Engineering (blog), January 4. https://nae.edu/266376/Who-Pays-for-DAC-The-Market-and-Policy-Landscape-for-Advancing-Direct-Air-Capture.

McCulloch, N., D. Natalini, N. Hossain, and P. Justino. 2022. "An Exploration of the Association between Fuel Subsidies and Fuel Riots." *World Development* 157 (September): 105935. doi:10.1016/j.worlddev.2022.105935.

McGreal, C. 2021. "ExxonMobil Lobbyists Filmed Saying Oil Giant's Support for Carbon Tax a PR Ploy." *The Guardian*, June 30. https://www.theguardian.com/us-news/2021/jun/30/exxonmobil-lobbyists-oil-giant-carbon-tax-pr-ploy.

McGreevy, M., and F. Baum. 2021. "Against the Odds, South Australia Is a Renewable Energy Powerhouse: How on Earth Did They Do It?" *The Conversation*, February 21. https://theconversation.com/against-the-odds-south-australia-is-a-renewable-energy-powerhouse-how-on-earth-did-they-do-it-153789.

McGreevy, M., C. MacDougall, M. Fisher, M. Henley, and F. Baum. 2020. "Expediting a Renewable Energy Transition in a Privatised Market via Public Policy: The Case of South Australia 2004–18." *Energy Policy* 148. doi:https://doi.org/10.1016/j.enpol.2020.111940.

McKerracher, C. 2022. "The World's Electric Vehicle Fleet Will Soon Surpass 20 Million." *Bloomberg*, April 8. https://www.bloomberg.com/news/articles/2022-04-08/plug-in-ev-fleet-will-soon-hit-a-20-million-milestone.

Meager, E. 2021. "Big US Firms Back Biden's Mandatory Climate Disclosure Plans." *Capital Monitor*, May 11. https://capitalmonitor.ai/institution/government/big-names-back-climate-disclosure-in-the-us/.

Mehaffy, M.W., J. Rogat, T. Litman, B. Gutierrez Figueroa, and T. Munshi. 2022. *The Road Forward*: *Cost-Effective Policy Measures to Decrease Emissions from Passenger Land Transport*. KTH Royal Institute of Technology, Copenhagen Centre on Energy Efficiency, UNEP DTU Partnership, and Sustasis Foundation. https://vtpi.org/trf2022.pdf.

Melodia, L., and K. Karlsson. 2022. "Energy Price Stability: The Peril of Fossil Fuels and the Promise of Renewables." New York: Roosevelt Institute. https://rooseveltinstitute.org/wp-content/uploads/2022/05/RI_EnergyPriceStability_IssueBrief_202205.pdf.

Mersmann, F., K. Holm Olsen, T. Wehnert, and Z. Boodoo. 2014. "Understanding Transformational Change in NAMAs: From Theory to Practice." Wuppertal, Germany: Wuppertal Institute for Climate, Environment, and Energy. https://www.transparency-partnership.net/sites/default/files/unep_dtu_nama_hr_web.pdf.

Micheli, M., A.S. Oyewo, M. Fasihi, C. Breyer, W. Weindorf, and P. Schmidt. Forthcoming. "E-Kerosene for Commercial Aviation: From Green Hydrogen and CO_2 from Direct Air Capture—Volumes, Area Demand, and Renewable Energy Competition in the United States and the European Union in 2050 Scenarios to Defossilize Aviation Fuel." Berlin: Deutsche Energie-Agentur GmbH.

Microsoft. 2021. "Microsoft Carbon Removal: Lessons from an Early Corporate Purchase." Cambridge, MA: Microsoft. https://query.prod.cms.rt.microsoft.com/cms/api/am/binary/RE4MDlc.

Miettinen, J., C. Shi, and S.C. Liew. 2012. "Two Decades of Destruction in Southeast Asia's Peat Swamp Forests." *Frontiers in Ecology and the Environment* 10 (3): 124–28. doi:10.1890/100236.

MIIT (Ministry of Industry and Information Technology of the People's Republic of China). 2022. "The Economic Operation of the Automobile Industry in December 2021." January 13. https://www.miit.gov.cn/gxsj/tjfx/zbgy/qc/art/2022/art_63f16aa43e3543c28bb285b7dc759eea.html.

Mildenberger, M. 2021. "The Development of Climate Institutions in the United States." *Environmental Politics* 30 (suppl. 1): 71–92. doi:10.1080/09644016.2021.1947445.

Minx, J.C., W.F. Lamb, R.M. Andrew, J.G. Canadell, M. Crippa, N. Döbbeling, P. Forster, et al. 2021. "A Comprehensive and Synthetic Dataset for Global, Regional, and National Greenhouse Gas Emissions by Sector, 1970–2018, with an Extension to 2019." *Earth System Science Data* 13 (11): 5213–52. doi:10.5194/essd-13-5213-2021.

Minx, J.C., W.F. Lamb, R.M. Andrew, J.G. Canadell, M. Crippa, N. Döbbeling, P. Forster, et al. 2022. "A Comprehensive and Synthetic Dataset for Global, Regional and National Greenhouse Gas Emissions by Sector, 1970–2018, with an Extension to 2019 [Data Set]." Zenodo. doi:10.5281/zenodo.6483002.

Mission Possible Partnership. 2022a. "Making Net-Zero Aviation Possible." https://missionpossiblepartnership.org/wp-content/uploads/2022/07/Making-Net-Zero-Aviation-possible.pdf.

Mission Possible Partnership. 2022b. "Making Zero-Emissions Trucking Possible." https://missionpossiblepartnership.org/wp-content/uploads/2022/07/Making-Zero-Emissions-Trucking-Possible.pdf.

Moffette, F., J. Alix-Garcia, K. Shea, and A.H. Pickens. 2021. "The Impact of Near-Real-Time Deforestation Alerts across the Tropics." *Nature Climate Change* 11 (2): 172–78. doi:10.1038/s41558-020-00956-w.

Molinario, G., M. Hansen, P. Potapov, A. Tyukavina, and S. Stehman. 2020. "Contextualizing Landscape-Scale Forest Cover Loss in the Democratic Republic of Congo (DRC) between 2000 and 2015." *Land* 9 (1): 23. doi:10.3390/land9010023.

Monasterolo, I., and M. Raberto. 2019. "The Impact of Phasing Out Fossil Fuel Subsidies on the Low-Carbon Transition." *Energy Policy* 124 (January): 355–70. doi:10.1016/j.enpol.2018.08.051.

Moore, M.-L., O. Tjornbo, E. Enfors, C. Knapp, J. Hodbod, J.A. Baggio, A. Norström, et al. 2014. "Studying the Complexity of Change: Toward an Analytical Framework for Understanding Deliberate Social-Ecological Transformations." *Ecology and Society* 19 (4): art54. doi:10.5751/ES-06966-190454.

Moore, F.C., K. Lacasse, K.J. Mach, Y.A. Shin, L.J. Gross, and B. Beckage. 2022. "Determinants of Emissions Pathways in the Coupled Climate-Social System." *Nature* 603 (7899): 103–11. doi:10.1038/s41586-022-04423-8.

Moran, D., K. Kanemoto, M. Jiborn, R. Wood, J. Többen, and K.C. Seto. 2018. "Carbon Footprints of 13,000 Cities." *Environmental Research Letters* 13 (6): 064041. doi:10.1088/1748-9326/aac72a.

Morawiecka, M., and J. Rosenow. 2022. "From Laggard to Leader: How Poland Became Europe's Fastest-Growing Heat Pump Market." Regulatory Assistance Project (blog), April 14. https://www.raponline.org/blog/from-laggard-leader-how-poland-became-europes-fastest-growing-heat-pump-market/.

Morris, L., S. Westfall, and R. Thebault. 2022. "Russia's Chokehold over Gas Could Send Europe Back to Coal." *Washington Post*, June 22. https://www.washingtonpost.com/world/2022/06/22/coal-plant-europe-germany-austria-netherlands-russia-gas/.

Motavalli, J. 2021. "Every Automaker's EV Plans through 2035 and Beyond." *Forbes*, October 4. https://www.forbes.com/wheels/news/automaker-ev-plans/.

Mrotzek, A., D. Michaelis, A. Günther, N. Wrage-Mönnig, and J. Couwenberg. 2020. "Mass Balances of a Drained and a Rewetted Peatland: On Former Losses and Recent Gains." *Soil Systems* 4 (1): 16. doi:10.3390/soilsystems4010016.

Muehlegger, E., and D. Rapson. 2019. "Understanding the Distributional Impacts of Vehicle Policy: Who Buys New and Used Electric Vehicles?" University of California, Davis, National Center for Sustainable Transportation. https://escholarship.org/uc/item/1q259456.

Mulligan, J., A. Rudee, K. Lebling, K. Levin, J. Anderson, and B. Christensen. 2020. "CarbonShot: Federal Policy Options for Carbon Removal in the United States." Washington, DC: World Resources Institute. https://www.wri.org/publication/carbonshot-federal-policy-options-for-carbon-removal-in-the-united-states.

Murray, N.J., T.A. Worthington, P. Bunting, S. Duce, V. Hagger, C.E. Lovelock, R. Lucas, et al. 2022. "High-Resolution Mapping of Losses and Gains of Earth's Tidal Wetlands." *Science* 376 (6594): 744–49. doi:10.1126/science.abm9583.

Mursyid, H., M.H. Daulay, A.A. Pratama, D. Laraswati, N. Novita, A. Malik, and A. Maryudi. 2021. "Governance Issues Related to the Management and Conservation of Mangrove Ecosystems to Support Climate Change Mitigation Actions in Indonesia." *Forest Policy and Economics* 133 (December): 102622. doi:10.1016/j.forpol.2021.102622.

Nadel, S., and A. Hinge. 2020. "Mandatory Building Performance Standards: A Key Policy for Achieving Climate Goals." ACEEE white paper. Washington, DC: American Council for an Energy-Efficient Economy. https://www.aceee.org/sites/default/files/pdfs/buildings_standards_6.22.2020_0.pdf.

Naik, G. 2021. "Companies, Investors Face New Pressure from Compulsory Disclosure of Climate Risk." SP Global (blog), August 25. https://www.spglobal.com/esg/insights/companies-investors-face-new-pressure-from-compulsory-disclosure-of-climate-risk.

NASEM (National Academies of Science, Engineering, and Medicine). 2019. "Negative Emissions Technologies and Reliable Sequestration: A Research Agenda." Washington, DC: NASEM. doi:10.17226/25259.

National BPS (Building Performance Standards) Coalition. 2022. "National BPS Coalition Commitment." https://nationalbpscoalition.org/.

Nepstad, D., D. McGrath, C. Stickler, A. Alencar, A. Azevedo, B. Swette, T. Bezerra, et al. 2014. "Slowing Amazon Deforestation through Public Policy and Interventions in Beef and Soy Supply Chains." *Science* 344 (6188): 1118–23. doi:10.1126/science.1248525.

Neslen, A. 2021. "Europe's Electric Car Revolution Risks Job Loss Backlash, Unions Warn." *Reuters*, September 6. https://www.reuters.com/article/climate-change-electric-workers/analysis-europes-electric-car-revolution-risks-job-loss-backlash-unions-warn-idUSL8N2Q23U4.

Neste. 2022. "California Low Carbon Fuel Standard Credit Price." https://www.neste.com/investors/market-data/lcfs-credit-price.

Newport, F. 2019. "Americans' Long-Standing Interest in Taxing the Rich." Gallup, February 22. https://news.gallup.com/opinion/polling-matters/247052/americans-long-standing-interest-taxing-rich.aspx.

Nicholas, S., and S. Basirat. 2021. "IEEFA: China's Peak Steel Emissions Shift Unlikely to Delay Carbon Reductions." Institute for Energy Economics and Financial Analysis, November 16. https://ieefa.org/ieefa-chinas-peak-steel-emissions-shift-unlikely-to-delay-carbon-reductions/.

Nicholls, D.L., H. McCann, D.Y. Strengers, and D.K. Bosomworth. 2017. "Electricity Pricing, Heatwaves & Household Vulnerability in Australia." Center for Urban Research, Royal Melbourne Institute of Technology. https://cur.org.au/cms/wp-content/uploads/2016/12/heatwaveshomeshealth-briefing-paper_rmit-2.pdf.

Nichols, M., and N. Lutsey. 2020. "Quantifying the Electric Vehicle Charging Infrastructure Gap in the United Kingdom." Washington, DC: International Council on Clean Transportation. https://theicct.org/publication/quantifying-the-electric-vehicle-charging-infrastructure-gap-in-the-united-kingdom/.

Nichols, M., D. Hall, and N. Lutsey. 2019. "Quantifying the Electric Vehicle Charging Infrastructure Gap across U.S. Markets." Washington, DC: International Council on Clean Transportation. https://theicct.org/publication/quantifying-the-electric-vehicle-charging-infrastructure-gap-across-u-s-markets/.

Niraula, R.R., H. Gilani, B.K. Pokharel, and F.M. Qamer. 2013. "Measuring Impacts of Community Forestry Program through Repeat Photography and Satellite Remote Sensing in the Dolakha District of Nepal." *Journal of Environmental Management* 126 (September): 20–29. doi:10.1016/j.jenvman.2013.04.006.

NITI (National Institute for Transforming India) Aayog. n.d. "Electric Vehicle Incentives." Accelerated E-Mobility Revolution for India's Transportation. https://e-amrit.niti.gov.in/electric-vehicle-incentives.

Nolte, C., A. Agrawal, K.M. Silvius, and B.S. Soares-Filho. 2013. "Governance Regime and Location Influence Avoided Deforestation Success of Protected Areas in the Brazilian Amazon." *Proceedings of the National Academy of Sciences* 110 (13): 4956–61. doi:10.1073/pnas.1214786110.

Norton, J., and Y. Ouyang. 2019. "Controls and Adaptive Management of Nitrification in Agricultural Soils." *Frontiers in Microbiology* 10. https://www.frontiersin.org/articles/10.3389/fmicb.2019.01931.

NYDF (New York Declaration on Forests) Assessment Partners. 2021. "Taking Stock of National Climate Action for Forests." Amsterdam: Climate Focus. https://forestdeclaration.org/resources/taking-stock-of-national-climate-action-for-forests/.

O'Brien, K., and L. Sygna. 2013. "Responding to Climate Change: The Three Spheres of Transformation." In *Proceedings: Transformation in a Changing Climate—International Conference*, 16–23. Oslo: University of Oslo. https://www.sv.uio.no/iss/english/research/projects/adaptation/publications/1-responding-to-climate-change---three-spheres-of-transformation_obrien-and-sygna_webversion_final.pdf.

OCI (Oil Change International). 2022. "Public Finance for Energy Database." https://energyfinance.org/.

Ocko, I.B., and S.P. Hamburg. 2022. "Climate Consequences of Hydrogen Emissions." *Atmospheric Chemistry and Physics* 22 (14): 9349–68. doi:10.5194/acp-22-9349-2022.

OECD (Organisation for Economic Co-operation and Development). 2017. "Investing in Climate, Investing in Growth." Paris: OECD. doi:https://doi.org/10.1787/9789264273528-en.

OECD. 2018. *Financing Climate Futures: Rethinking Infrastructure.* Paris: OECD. doi:10.1787/9789264308114-en.

OECD. 2021a. "Forward-Looking Scenarios of Climate Finance Provided and Mobilised by Developed Countries in 2021–2025." Paris: OECD. doi:10.1787/a53aac3b-en.

OECD. 2021b. "OECD Companion to the Inventory of Support Measures for Fossil Fuels, 2021." Paris: OECD. doi:https://doi.org/10.1787/e670c620-en.

OECD. 2021c. "OECD Secretary-General Tax Report to G20 Finance Ministers and Central Bank Governors." Paris: OECD. www.oecd.org/tax/oecd-secretary-general-tax-report-g20-finance-ministers-february-2021.pdf.

OECD. 2022a. "Aggregate Trends of Climate Finance Provided and Mobilised by Developed Countries in 2013–2020." Paris: OECD. https://www.oecd.org/climate-change/finance-usd-100-billion-goal.

OECD. 2022b. "Support for Fossil Fuels Almost Doubled in 2021, Slowing Progress toward International Climate Goals, According to New Analysis from OECD and IEA." Paris: OECD, August 29. https://www.oecd.org/newsroom/support-for-fossil-fuels-almost-doubled-in-2021-slowing-progress-toward-international-climate-goals-according-to-new-analysis-from-oecd-and-iea.htm.

OECD and IISD (International Institute for Sustainable Development). 2021. "Fossil Fuel Subsidy Tracker." Paris: OECD. 2021. https://fossilfuelsubsidytracker.org/.

OECD, World Bank, and UN Environment Programme. 2018. "Financing Climate Futures: Rethinking Infrastructure." Paris: OECD. https://doi.org/10.1787/9789264308114-en.

Office of Governor Newsom. 2022. "California Leads the Nation's ZEV Market, Surpassing 1 Million Electric Vehicles Sold." February 25. https://www.gov.ca.gov/2022/02/25/california-leads-the-nations-zev-market-surpassing-1-million-electric-vehicles-sold/#:~:text=Over%20the%20past%2010%20years,other%20zero%2Demission%20vehicle%20metrics%2C.

Oliver, P., A. Clark, and C. Meattle. 2018. "Global Climate Finance: An Updated View 2018." London: Climate Policy Initiative. https://www.climatepolicyinitiative.org/publication/global-climate-finance-an-updated-view-2018/.

Olsson, P., C. Folke, and T. Hahn. 2004. "Social-Ecological Transformation for Ecosystem Management: The Development of Adaptive Co-management of a Wetland Landscape in Southern Sweden." *Ecology and Society* 9 (4). doi:10.5751/ES-00683-090402.

Olsthoorn, M., J. Schleich, L. Javaudin, and Y. Jiang. 2016. "Barriers to Energy Efficiency in Developing Countries' Industry Sectors: Empirical Evidence from Clean Development Mechanism (CDM) Projects." *Journal of Energy and Development* 42 (1/2): 189–221.

OpenNEM (National Electricity Market). 2022. "Energy—South Australia." https://opennem.org.au/energy/sa1/?range=all&interval=1y.

OpenStreetMap Foundation. n.d. "OpenStreetMap." https://www.openstreetmap.org/.

Ortiz, J., N. Casquero-Modrego, and J. Salom. 2019. "Health and Related Economic Effects of Residential Energy Retrofitting in Spain." *Energy Policy* 130 (July): 375–88. doi:10.1016/j.enpol.2019.04.013.

Otto, I.M., J.F. Donges, R. Cremades, A. Bhowmik, R.J. Hewitt, W. Lucht, J. Rockström, et al. 2020. "Social Tipping Dynamics for Stabilizing Earth's Climate by 2050." *Proceedings of the National Academy of Sciences* 117 (5): 2354–65. doi:10.1073/pnas.1900577117.

Oxford University Economic Recovery Project. 2022. "Global Recovery Observatory." https://recovery.smithschool.ox.ac.uk/tracking/.

Oyono, P.R. 2021. "Poverty, Tenure Security, and Landscape Governance: Exploring Inextricable Interdependencies for Science, Policy, and Action." Washington, DC: International Food Policy Research Institute. doi:10.2499/p15738coll2.134791.

Page, S.E., J.O. Rieley, and C.J. Banks. 2011. "Global and Regional Importance of the Tropical Peatland Carbon Pool: Tropical Peatland Carbon Pool." *Global Change Biology* 17 (2): 798–818. doi:10.1111/j.1365-2486.2010.02279.x.

Paltsev, S., J. Morris, H. Kheshgi, and H. Herzog. 2021. "Hard-to-Abate Sectors: The Role of Industrial Carbon Capture and Storage (CCS) in Emission Mitigation." *Applied Energy* 300 (February). doi:10.1016/j.apenergy.2021.117322.

Patterson, J., K. Schulz, J. Vervoort, S. van der Hel, O. Widerberg, C. Adler, M. Hurlbert, et al. 2017. "Exploring the Governance and Politics of Transformations towards Sustainability." *Environmental Innovation and Societal Transitions* 24 (September): 1–16. doi:10.1016/j.eist.2016.09.001.

PCC (Presidential Climate Commission). 2022. "A Framework for a Just Transition in South Africa." https://pccommissionflow.imgix.net/uploads/images/A-Just-Transition-Framework-for-South-Africa-2022.pdf.

Pearl-Martinez, R., and J.C. Stephens. 2016. "Toward a Gender Diverse Workforce in the Renewable Energy Transition." *Sustainability: Science, Practice and Policy* 12 (1): 8–15. doi:10.1080/15487733.2016.11908149.

Pekanov, A., and M. Schratzenstaller. 2019. "A Global Financial Transaction Tax: Theory, Practice and Potential Revenues." Vienna: Österreichisches Institut für Wirtschaftsforschung. https://www.wifo.ac.at/jart/prj3/wifo/main.jart?content-id=1454619331110&publikation_id=61805&detail-view=yes.

Pendleton, L., D.C. Donato, B.C. Murray, S. Crooks, W.A. Jenkins, S. Sifleet, C. Craft, et al. 2012. "Estimating Global 'Blue Carbon' Emissions from Conversion and Degradation of Vegetated Coastal Ecosystems." Edited by S. Thrush. *PLoS ONE* 7 (9): e43542. doi:10.1371/journal.pone.0043542.

Pendrill, F., U.M. Persson, J. Godar, and T. Kastner. 2019a. "Deforestation Displaced: Trade in Forest-Risk Commodities and the Prospects for a Global Forest Transition." *Environmental Research Letters* 14 (5): 055003. doi:10.1088/1748-9326/ab0d41.

Pendrill, F., U.M. Persson, J. Godar, T. Kastner, D. Moran, S. Schmidt, and R. Wood. 2019b. "Agricultural and Forestry Trade Drives Large Share of Tropical Deforestation Emissions." *Global Environmental Change* 56 (May): 1–10. doi:10.1016/j.gloenvcha.2019.03.002.

Petersen, R., C. Davis, and M. Herold. 2018. "Ending Tropical Deforestation: Tropical Forest Monitoring: Exploring the Gaps between What Is Required and What Is Possible for REDD+ and Other Initiatives." Washington, DC: World Resources Institute. https://www.wri.org/research/ending-tropical-deforestation-tropical-forest-monitoring-exploring-gaps-between-what.

Pevec, D., J. Babic, A. Carvalho, Y. Ghiassi-Farrokhfal, W. Ketter, and V. Podobnik. 2020. "A Survey-Based Assessment of How Existing and Potential Electric Vehicle Owners Perceive Range Anxiety." *Journal of Cleaner Production* 276 (December): 122779. doi:10.1016/j.jclepro.2020.122779.

Pham, T.T., T.P. Vu, T.L. Hoang, T.L.C. Dao, D.T. Nguyen, DC Pham, L.H.T. Dao, et al. 2022. "The Effectiveness of Financial Incentives for Addressing Mangrove Loss in Northern Vietnam." *Frontiers in Forests and Global Change* 4 (January): 709073. doi:10.3389/ffgc.2021.709073.

Phillips, M. 2022. "Inflation Surges to 8.5%, Highest in over 40 Years." *Axios*, April 12. https://www.axios.com/2022/04/12/inflation-surges-march.

Piggot, G., C. Verkuijl, H. van Asselt, and M. Lazarus. 2020. "Curbing Fossil Fuel Supply to Achieve Climate Goals." *Climate Policy* 20 (8): 881–87. doi:10.1080/14693062.2020.1804315.

Plaza, M.G., S. Mart, and F. Rubiera. 2020. "CO_2 Capture, Use, and Storage in the Cement Industry: State of the Art and Expectations." *Energies* 13 (5692). doi:10.3390/en13215692.

Polar, V. 2021. "Women Hold the Seeds of a Stronger Food System for Peru / Las Mujeres Alimentarán Nuestro Futuro." CGIAR Gender Platform, March 17. https://gender.cgiar.org/news-events/women-hold-seeds-stronger-food-system-peru.

Pollin, R., and B. Callaci. 2019. "The Economics of Just Transition: A Framework for Supporting Fossil Fuel–Dependent Workers and Communities in the United States." *Labor Studies Journal* 44 (2): 93–138. doi:10.1177/0160449X18787051.

Poorter, L., D. Craven, C.C. Jakovac, M.T. van der Sande, L. Amissah, F. Bongers, R.L. Chazdon, et al. 2021. "Multidimensional Tropical Forest Recovery." *Science* 374 (6573): 1370–76. doi:10.1126/science.abh3629.

PORT PC. 2022. "80% Increase in Sales of Heat Pumps for Heating Buildings in 2021." *PORT PC* (blog), February 22. https://portpc.pl/port-pc-wzrost-o-80-sprzedazy-pomp-ciepla-do-ogrzewania-budynkow-w-2021-r/.

Potapov, P., M.C. Hansen, A. Pickens, A. Hernandez-Serna, A. Tyukavina, S. Turubanova, V. Zalles, et al. 2022a. "The Global 2000–2020 Land Cover and Land Use Change Dataset Derived from the LANDSAT Archive: First Results." *Frontiers in Remote Sensing* 3. https://www.frontiersin.org/articles/10.3389/frsen.2022.856903.

Potapov, P., S. Turubanova, M.C. Hansen, A. Tyukavina, V. Zalles, A. Khan, X.-P. Song, et al. 2022b. "Global Maps of Cropland Extent and Change Show Accelerated Cropland Expansion in the Twenty-First Century." *Nature Food* 3 (1): 19–28. doi:10.1038/s43016-021-00429-z.

Prime Minister's Office (United Kingdom). 2021. "Over 100 Leaders Make Landmark Pledge to End Deforestation at COP26." November 2. https://www.gov.uk/government/news/over-100-leaders-make-landmark-pledge-to-end-deforestation-at-cop26.

PR Newswire. 2022. "Twelve and Alaska Airlines to Collaborate with Microsoft to Advance Sustainable Aviation Fuel Derived from Recaptured CO_2 and Renewable Energy." July 14. https://www.prnewswire.com/news-releases/twelve-and-alaska-airlines-to-collaborate-with-microsoft-to-advance-sustainable-aviation-fuel-derived-from-recaptured-co2-and-renewable-energy-301586420.html.

Pucher, J., and R. Buehler. 2008. "Making Cycling Irresistible: Lessons from the Netherlands, Denmark and Germany." *Transport Reviews* 28 (4): 495–528. doi:10.1080/01441640701806612.

Purnomo, E.P., R. Ramdani, Agustiyara, Q.P.V. Tomaro, and G.S. Samidjo. 2019. "Land Ownership Transformation before and after Forest Fires in Indonesian Palm Oil Plantation Areas." *Journal of Land Use Science* 14 (1): 37–51. doi:10.1080/1747423X.2019.1614686.

Qadrdan, M., M. Cheng, J. Wu, and N. Jenkins. 2017. "Benefits of Demand-Side Response in Combined Gas and Electricity Networks." *Applied Energy* 192 (April): 360–69. doi:10.1016/j.apenergy.2016.10.047.

Race to Zero. 2021a. "Race to Zero Breakthroughs." Blog, January 28. https://racetozero.unfccc.int/ breakthroughs/.

Race to Zero. 2021b. "Commitment on Eliminating Agricultural Commodity-Driven Deforestation." November 2. https://racetozero.unfccc.int/system/nature-and-tackling-deforestation/.

Race to Zero, Nexial, and Laudes Foundation. 2022. "Built Environment System Map." https://nexial.co/maps/rtzbe/#/?stop=all&resetvid=all&on=Welcome&panx=4600&pany=3500&zoom=1.0&wpane=300&epane=320&unoInfo=Welcome.

Radowitz, B. 2021. "Hydrogen Hubs to Boost Sector with Highest Concentration in Europe: Fitch Solutions." *Recharge*, August 6. https://www.rechargenews.com/energy-transition/hydrogen-hubs-to-boost-sector-with-highest-concentration-in-europe-fitch-solutions/2-1-1049313.

Ravillard, P., J.E. Chueca, M. Weiss, and M. Carvalho Metanias Hallack. 2021. "Implications of the Energy Transition on Employment: Today's Results, Tomorrow's Needs." Washington, DC: Inter-American Development Bank. doi:10.18235/0003765.

Ray, R., K. Gallagher, and W. Kring. 2020. "IMF Austerity since the Global Financial Crisis: New Data, Same Trend, and Similar Determinants." Boston University Global Development Policy Center. https://www.bu.edu/gdp/files/2020/11/IMF-Austerity-Since-the-Global-Financial-Crisis-WP.pdf.

Reuters Staff. 2020. "China to Make National Carbon Trading 'Breakthrough' by Year-End: Official." January 14. https://www.reuters.com/article/us-china-carbon/china-to-make-national-carbontrading-breakthrough-by-year-end-official-idUSKBN1ZD05N.

Reydon, B.P., V.B. Fernandes, and T.S. Telles. 2020. "Land Governance as a Precondition for Decreasing Deforestation in the Brazilian Amazon." *Land Use Policy* 94 (May): 104313. doi:10.1016/j.landusepol.2019.104313.

Reyers, B., C. Folke, M.-L. Moore, R. Biggs, and V. Galaz. 2018. "Social-Ecological Systems Insights for Navigating the Dynamics of the Anthropocene." *Annual Review of Environment and Resources* 43 (1): 267–89. doi:10.1146/annurev-environ-110615-085349.

Ricciardi, V., N. Ramankutty, Z. Mehrabi, L. Jarvis, and B. Chookolingo. 2018. "How Much of the World's Food Do Smallholders Produce?" *Global Food Security* 17 (June): 64–72. doi:10.1016/j.gfs.2018.05.002.

Richter, F. 2020. "These Are the Top 10 Manufacturing Countries in the World." World Economic Forum, February 25. https://www.weforum.org/agenda/2020/02/countries-manufacturing-trade-exports-economics/.

Rissman, J., C. Bataille, E. Masanet, N. Aden, W.R. Morrow, N. Zhou, N. Elliott, et al. 2020. "Technologies and Policies to Decarbonize Global Industry: Review and Assessment of Mitigation Drivers through 2070." *Applied Energy* 266 (May): 114848. doi:10.1016/j.apenergy.2020.114848.

Ritchie, H., M. Roser, and P. Rosado. 2020a. "CO_2 and Greenhouse Gas Emissions." *Our World in Data*, August. https://ourworldindata.org/co2-and-other-greenhouse-gas-emissions.

Ritchie, H., M. Roser, and P. Rosado. 2020b. "Access to Energy." *Our World in Data*, November 28. https://ourworldindata.org/energy-access.

Roberts, D. 2019. "Cars Dominate Cities Today: Barcelona Has Set Out to Change That." *Vox*, September 11. https://www.vox.com/energy-and-environment/2019/4/8/18273893/barcelona-spain-urban-planning-cars.

Rodríguez-de-Francisco, J.C., C. del Cairo, D. Ortiz-Gallego, J.S. Velez-Triana, T. Vergara-Gutiérrez, and J. Hein. 2021. "Post-conflict Transition and REDD+ in Colombia: Challenges to Reducing Deforestation in the Amazon." *Forest Policy and Economics* 127 (June): 102450. doi:10.1016/j.forpol.2021.102450.

Roe, S., C. Streck, M. Obersteiner, S. Frank, B. Griscom, L. Drouet, O. Fricko, et al. 2019. "Contribution of the Land Sector to a 1.5°C World." *Nature Climate Change* 9 (11): 817–28. doi:10.1038/s41558-019-0591-9.

Roe, S., C. Streck, R. Beach, J. Busch, M. Chapman, V. Daioglou, A. Deppermann, et al. 2021. "Land-Based Measures to Mitigate Climate Change: Potential and Feasibility by Country." *Global Change Biology* 27 (23): 6025–58. doi:10.1111/gcb.15873.

Roelofsen, O., K. Somers, E. Speelman, and M. Witteveen. 2020. "Plugging In: What Electrification Can Do for Industry." McKinsey & Company, May 28. https://www.mckinsey.com/industries/electric-power-and-natural-gas/our-insights/plugging-in-what-electrification-can-do-for-industry.

Rosenow, J., and D. Gibb. 2022. "How Heat Pump Sales Are Starting to Take Off around the World." *Carbon Brief* (blog), March 1. https://www.carbonbrief.org/guest-post-how-heat-pump-sales-are-starting-to-take-off-around-the-world.

Rosentreter, J.A., D.T. Maher, D.V. Erler, R.H. Murray, and B.D. Eyre. 2018. "Methane Emissions Partially Offset 'Blue Carbon' Burial in Mangroves." *Science Advances* 4 (6): eaao4985. doi:10.1126/sciadv.aao4985.

Rosentreter, J.A., A.V. Borges, B.R. Deemer, M.A. Holgerson, S. Liu, C. Song, J. Melack, et al. 2021. "Half of Global Methane Emissions Come from Highly Variable Aquatic Ecosystem Sources." *Nature Geoscience* 14 (4): 225–30. doi:10.1038/s41561-021-00715-2.

Rothrock, P., K. Ellis, and L. Weatherer. 2022. "Corporate Progress on No Deforestation and 'Nature Positive' Post 2020." Washington, DC: Forest Trends. https://www.forest-trends.org/publications/corporate-progress-on-no-deforestation-and-nature-positive-post-2020/.

Rotich, B., E. Mwangi, and S. Lawry. 2016. "Where Land Meets Sea: A Global Review of the Governance and Tenure Dimensions of Coastal Mangrove Forests." Washington, DC: U.S. Agency for International Development. https://www.cifor.org/knowledge/publication/6376/.

Rowe, S.J., S.M. Hickey, A. Jonker, M.K. Hess, P. Janssen, T. Johnson, B. Bryson, et al. 2019. "Selection for Divergent Methane Yield in New Zealand Sheep: A Ten-Year Perspective." *Proceedings of the 23rd Conference of the Association for the Advancement of Animal Breeding and Genetics (AAABG), Armidale, New South Wales, Australia, 27th October–1st November 2019*, 306–9.

Rowlingson, K., A. Sood, and T. Tu. 2021. "Public Attitudes to a Wealth Tax: The Importance of 'Capacity to Pay.'" *Fiscal Studies* 42 (3–4): 431–55. doi:10.1111/1475-5890.12282.

Ryan, J. 2022. "Electric Vehicles Have Surged in Washington State: But Gas Cars Still Dominate." KUOW / National Public Radio. 2022. https://www.kuow.org/stories/electric-vehicle-sales-have-surged-in-wa-but-gas-cars-still-dominate.

Sacca, C. 2022. "Clean Up on Aisle Earth." Lowercarbon Capital, April 14. https://lowercarboncapital.com/2022/04/14/clean-up-on-aisle-earth/.

SAFA (South Australian Government Financing Authority). 2020. "Renewable Energy." Adelaide: SAFA. https://www.safa.sa.gov.au/environmental-s-governance/energy.

Saha, D., R. Shrestha, and J. Feldmann. 2021. "Designing the Next Generation of Federal Tax Credits for Low-Carbon Technologies." World Resources Institute. doi:10.46830/wriwp.20.00111.

Salcedo–La Viña, C., and R. Giovarelli. 2021. "On Equal Ground: Promising Practices for Realizing Women's Rights in Collectively Held Lands." Washington, DC: World Resources Institute. https://www.wri.org/research/equal-ground-promising-practices-realizing-womens-rights-collectively-held-lands.

Samenow, J., and K. Patel. 2022. "It's 70 Degrees Warmer than Normal in Eastern Antarctica: Scientists Are Flabbergasted." *Washington Post*, March 18. https://www.washingtonpost.com/weather/2022/03/18/antarctica-heat-wave-climate-change/.

Sanchez, L., R. Bridle, V. Corkal, P. Gass, A. Geddes, I. Gerasimchuk, J. Kuehl, et al. 2021. "Achieving a Fossil-Free Recovery." Winnipeg, Canada: International Institute for Sustainable Development. https://www.iisd.org/publications/achieving-fossil-free-recovery.

Sandalow, D., R. Aines, P. Keleman, C. McCormick, I. Power, B. Schmidt, and S. Wilson. 2021. "Carbon Mineralization Roadmap." Tokyo: Innovation for Cool Earth Forum. https://www.icef.go.jp/pdf/summary/roadmap/icef2021_roadmap.pdf.

Sands, L. 2022. "Pakistan Floods: One Third of Country Is Under Water—Minister." BBC, August 30. https://www.bbc.com/news/world-europe-62712301.

Santika, T., K.A. Wilson, S. Budiharta, A. Kusworo, E. Meijaard, E.A. Law, R. Friedman, et al. 2019. "Heterogeneous Impacts of Community Forestry on Forest Conservation and Poverty Alleviation: Evidence from Indonesia." Edited by J. McPherson. *People and Nature* 1 (2): 204–19. doi:10.1002/pan3.25.

Sasmito, S.D., P. Taillardat, J.N. Clendenning, C. Cameron, D.A. Friess, D. Murdiyarso, and L.B. Hutley. 2019. "Effect of Land-Use and Land-Cover Change on Mangrove Blue Carbon: A Systematic Review." *Global Change Biology* 25 (12): 4291–4302. doi:10.1111/gcb.14774.

Sawhill, I., and C. Pulliam. 2019. "Americans Want the Wealthy and Corporations to Pay More Taxes, but Are Elected Officials Listening?" Brookings, 2019. https://www.brookings.edu/blog/up-front/2019/03/14/americans-want-the-wealthy-and-corporations-to-pay-more-taxes-but-are-elected-officials-listening/.

SBTi (Science Based Targets initiative). 2021. "SBTi Corporate Net-Zero-Standard." https://sciencebasedtargets.org/resources/files/Net-Zero-Standard.pdf.

SBTi. 2022. "Companies Taking Action." https://sciencebasedtargets.org/companies-taking-action.

SCF (UN Framework Convention on Climate Change Standing Committee on Finance). 2014. *2014 Biennial Assessment and Overview of Climate Finance Report*. Bonn, Germany: SCF. http://unfccc.int/files/cooperation_and_support/financial_mechanism/standing_committee/application/pdf/2014_biennial_assessment_and_overview_of_climate_finance_flows_report_web.pdf.

Schalatek, L. 2012. "Democratizing Climate Finance Governance and the Public Funding of Climate Action." *Democratization* 19 (5): 951–73. doi:10.1080/13510347.2012.709690.

Scharlemann, J.P., E.V. Tanner, R. Hiederer, and V. Kapos. 2014. "Global Soil Carbon: Understanding and Managing the Largest Terrestrial Carbon Pool." *Carbon Management* 5 (1): 81–91. doi:10.4155/cmt.13.77.

Scherer, S. 2022. "Canada Creates Carbon-Capture Incentives, Critical Mineral Plan to Cut Emissions." Reuters, April 7. https://www.reuters.com/business/sustainable-business/canada-creates-carbon-capture-incentives-critical-mineral-plan-cut-emissions-2022-04-07/.

Schleicher, J., C.A. Peres, T. Amano, W. Llactayo, and N. Leader-Williams. 2017. "Conservation Performance of Different Conservation Governance Regimes in the Peruvian Amazon." *Scientific Reports* 7 (1): 11318. doi:10.1038/s41598-017-10736-w.

Schmidt, T.S., T. Matsuo, and A. Michaelowa. 2017. "Renewable Energy Policy as an Enabler of Fossil Fuel Subsidy Reform? Applying a Socio-technical Perspective to the Cases of South Africa and Tunisia." *Global Environmental Change* 45 (July): 99–110. doi:10.1016/j.gloenvcha.2017.05.004.

Schuerch, M., T. Spencer, S. Temmerman, M.L. Kirwan, C. Wolff, D. Lincke, C.J. McOwen, et al. 2018. "Future Response of Global Coastal Wetlands to Sea-Level Rise." *Nature* 561 (7722): 231–34. doi:10.1038/s41586-018-0476-5.

Schumer, C., and K. Lebling. 2022. "How Are Countries Counting on Carbon Removal to Meet Climate Goals?" *Insights* (blog), March 16. Washington, DC: World Resources Institute. https://www.wri.org/insights/carbon-removal-countries-climate-goals.

Schumer, C., J. Jaeger, S. Boehm, L. Jeffery, K. Levin, J. Hecke, C. Fyson, et al. 2022. "Methodology Underpinning the State of Climate Action Series." Berlin and Cologne, Germany, San Francisco, CA, and Washington, DC: Bezos Earth Fund, Climate Action Tracker, Climate Analytics, ClimateWorks Foundation, NewClimate Institute, the United Nations Climate Change High-Level Champions, and World Resources Institute. doi.org/10.46830/writn.22.00064.

Searchinger, T., C. Hanson, R. Waite, and J. Ranganathan. 2019a. "10 Breakthrough Technologies Can Help Feed the World without Destroying It." World Resources Institute (blog), July. https://www.wri.org/insights/10-breakthrough-technologies-can-help-feed-world-without-destroying-it.

Searchinger, T., R. Waite, C. Hanson, J. Ranganathan, P. Dumas, and E. Matthews. 2019b. *World Resources Report*: *Creating a Sustainable Food Future—A Menu of Solutions to Feed Nearly 10 Billion People by 2050*. Washington, DC: World Resources Institute. www.sustainablefoodfuture.org.

Searchinger, T., C. Malins, P. Dumas, D. Baldock, J. Glauber, T. Jayne, J. Huang, and P. Marenya. 2020. "Revising Public Agricultural Support to Mitigate Climate Change." Washington, DC: World Bank Group. doi:10.1596/33677.

Searchinger, T., J. Zionts, S. Wirsenius, L. Peng, T. Beringer, and P. Dumas. 2021. *A Pathway to Carbon Neutral Agriculture in Denmark*. Washington, DC: World Resources Institute. https://www.wri.org/research/pathway-carbon-neutral-agriculture-denmark.

SEforAll (Sustainable Energy for All) and CPI (Climate Policy Initiative). 2020. "Energizing Finance 2020: Understanding the Landscape." https://www.seforall.org/system/files/2020-11/EF-2020-UL-SEforALL_0.pdf.

SEI (Stockholm Environment Institute), International Institute for Sustainable Development, Overseas Development Institute, E3G, and UN Environment Programme. 2020. *The Production Gap Report*: *2020 Special Report*. http://productiongap.org/2020report.

Seto, K.C., S.J. Davis, R.B. Mitchell, E.C. Stokes, G. Unruh, and D. Ürge-Vorsatz. 2016. "Carbon Lock-In: Types, Causes, and Policy Implications." *Annual Review of Environment and Resources* 41 (1): 425–52. doi:10.1146/annurev-environ-110615-085934.

Seymour, F. 2021. "2021 Must Be a Turning Point for Forests: 2020 Data Shows Us Why." World Resources Institute (blog), March 31. https://www.wri.org/insights/2021-must-be-turning-point-forests-2020-data-shows-us-why.

Seymour, F., and J. Busch. 2016. *Why Forests? Why Now? The Science, Economics, and Politics of Tropical Forests and Climate Change*. Washington DC: Center for Global Development.

Shang, B. 2021. "The Poverty and Distributional Impacts of Carbon Pricing: Channels and Policy Implications." Washington, DC: International Monetary Fund. file:///C:/Users/Neelam.Singh/OneDrive%20-%20World%20Resources%20Institute/Desktop/wpiea2021172-print-pdf.pdf.

Shapiro, S.L. 2019. "Basalt as an Alternative to Limestone in the Production of Portland Cement." *International Journal of High School Research* 1 (2): 17–20. doi:10.36838/v1i2.4.

Sharpe, S., and T.M. Lenton. 2021. "Upward-Scaling Tipping Cascades to Meet Climate Goals: Plausible Grounds for Hope." *Climate Policy* 21 (4): 421–33. doi:10.1080/14693062.2020.1870097.

Shell and Deloitte. 2020. "Decarbonising Shipping: All Hands on Deck." The Hague: Shell. https://www.shell.com/promos/energy-and-innovation/decarbonising-shipping-all-hands-on-deck/_jcr_content.stream/1594141914406/b4878c899602611f78d36655ebff06307e49d0f8/decarbonising-shipping-report.pdf.

Shih, G., S. Hussain, and A. Jeong. 2022. "Pakistan Reels from 'Apocalyptic' Floods, Pleads for International Aid." *Washington Post*, August 30. https://www.washingtonpost.com/world/2022/08/30/pakistan-flooding-underwater-monsoon/.

Shorrocks, A., J. Davies, and R. Lluberas. 2021. "Global Wealth Databook 2021." Zurich: Credit Suisse. https://www.credit-suisse.com/media/assets/corporate/docs/about-us/research/publications/global-wealth-databook-2021.pdf.

Sikarwar, V.S., A. Reichert, M. Jeremias, and V. Manovic. 2021. "COVID-19 Pandemic and Global Carbon Dioxide Emissions: A First Assessment." *Science of the Total Environment* 794 (November): 148770. doi:10.1016/j.scitotenv.2021.148770.

Singh, S. 2021. "Boeing Doesn't Think Hydrogen Will Power Its Next Aircraft." *Simple Flying*, January 27. https://simpleflying.com/boeing-no-hydrogen-aircraft/.

SLOCAT (Partnership on Sustainable Low-Carbon Transport). 2021. "Tracking Trends in a Time of Change: The Need for Radical Action towards Sustainable Transport Decarbonisation." https://tcc-gsr.com/transport-demand/low-carbon-transport-pathways/.

SLOCAT. 2022. "E-Mobility Trends and Targets." https://slocat.net/e-mobility-targets/.

Slough, T., J. Kopas, and J. Urpelainen. 2021. "Satellite-Based Deforestation Alerts with Training and Incentives for Patrolling Facilitate Community Monitoring in the Peruvian Amazon." *Proceedings of the National Academy of Sciences* 118 (29): e2015171118. doi:10.1073/pnas.2015171118.

Sommer, J.M., M. Restivo, and J.M. Shandra. 2020. "The United States, Bilateral Debt-for-Nature Swaps, and Forest Loss: A Cross-National Analysis." *Journal of Development Studies* 56 (4): 748–64. doi:10.1080/00220388.2018.1563683.

Sonter, L.J., M.C. Dade, J.E.M. Watson, and R.K. Valenta. 2020. "Renewable Energy Production Will Exacerbate Mining Threats to Biodiversity." *Nature Communications* 11 (1): 4174. doi:10.1038/s41467-020-17928-5.

Spack, M., and J. Finkelstein. 2014. "Travel Demand Management: An Analysis of the Effectiveness of TDM Plans in Reducing Traffic and Parking in the Minneapolis–St. Paul Metropolitan Area." Spack Consulting. http://www.mikeontraffic.com/wp-content/uploads/2014/01/TDM-Plan-Effectiveness-Study.pdf.

Spalding, M.D., and M. Leal. 2021. *The State of the World's Mangroves, 2021*. Washington, DC: Global Mangrove Alliance. https://www.mangrovealliance.org/wp-content/uploads/2021/07/The-State-of-the-Worlds-Mangroves-2021-FINAL.pdf.

SPIUG (Association of Heating Appliances Manufacturers and Importers in Poland). 2022. "Heating Appliances Market in Poland in 2021." https://www.slideshare.net/SPIUG/heating-appliances-market-in-poland-2021.

Stacey, B. 2021. "Making Blended Finance Work for Agri-SMEs: Lessons Learned from Selected Case Studies." Organisation for Economic Co-operation and Development, May 20. http://www.oecd.org/officialdocuments/publicdisplaydocumentpdf/?cote=DCD(2021)7&docLanguage=en.

Stapleton, L., S. Sorrell, and T. Schwanen. 2017. "Peak Car and Increasing Rebound: A Closer Look at Car Travel Trends in Great Britain." *Transportation Research Part D: Transport and Environment* 53 (June): 217–33. doi:10.1016/j.trd.2017.03.025.

Steckel, J.C., L. Missbach, N. Ohlendorf, S. Feindt, and M. Kalkuhl. 2022. "Effects of the Energy Price Crisis on European Households." Mercator Research Institute on Global Commons and Climate Change. https://www.mcc-berlin.net/fileadmin/data/C18_MCC_Publications/2022_MCC_Effects_of_the_energy_price_crisis_on_European_households.pdf.

Steer, A., and C. Hanson. 2021. "Corporate Financing of Nature Based Solutions: What Next?" *Insights* (blog), April 5. https://www.wri.org/insights/corporate-financing-nature-based-solutions-what-next.

Steffen, W., J. Rockström, K. Richardson, T.M. Lenton, C. Folke, D. Liverman, C.P. Summerhayes, et al. 2018. "Trajectories of the Earth System in the Anthropocene." *Proceedings of the National Academy of Sciences* 115 (33): 8252–59. doi:10.1073/pnas.1810141115.

Sterl, S., M. Hagemann, H. Fekete, N. Höhne, K. Wouters, Y. Deng, K. Blok, et al. 2017. "Kick-Starting Global Decarbonization: It Only Takes a Few Actors to Get the Ball Rolling." Berlin: NewClimate Institute, Ecofys, Climate Analytics, and ClimateWorks Foundation. https://climateactiontracker.org/documents/354/CAT_2017-04-20_Faster-Cleaner-2_Technical-Report.pdf.

Stern, N. 2006. "The Economics of Climate Change: The Stern Review." London: HM Treasury. https://webarchive.nationalarchives.gov.uk/20100407172811/http://www.hm-treasury.gov.uk/stern_review_report.htm.

Stevens, C., R. Winterbottom, J. Springer, and K. Reytar. 2014. "Securing Rights, Combating Climate Change: How Strengthening Community Forest Rights Mitigates Climate Change." Washington, DC: World Resources Institute. https://www.wri.org/research/securing-rights-combating-climate-change.

Strack, M., S.J. Davidson, T. Hirano, and C. Dunn. 2022. "The Potential of Peatlands as Nature-Based Climate Solutions." *Current Climate Change Reports* 8 (3): 71–82. doi:10.1007/s40641-022-00183-9.

Strambo, C., and A.C. González Espinosa. 2020. "Extraction and Development: Fossil Fuel Production Narratives and Counternarratives in Colombia." *Climate Policy* 20 (8): 931–48. doi:10.1080/14693062.2020.1719810.

Su, J., D.A. Friess, and A. Gasparatos. 2021. "A Meta-analysis of the Ecological and Economic Outcomes of Mangrove Restoration." *Nature Communications* 12 (1): 5050. doi:10.1038/s41467-021-25349-1.

Sumaila, U.R., M. Walsh, K. Hoareau, A. Cox, P. Abdallah, W. Akpalu, Z. Anna, et al. 2020. "Ocean Finance: Financing the Transition to a Sustainable Ocean Economy." Washington, DC: World Resources Institute. https://oceanpanel.org/sites/default/files/2020-10/Ocean%20Finance%20Full%20Paper.pdf.

Sun, H., B.K. Edziah, A.K. Kporsu, S.A. Sarkodie, and F. Taghizadeh-Hesary. 2021. "Energy Efficiency: The Role of Technological Innovation and Knowledge Spillover." *Technological Forecasting and Social Change* 167 (June): 120659. doi:10.1016/j.techfore.2021.120659.

Sunderland, L., and A. Jahn. 2021. "Considering Minimum Energy Performance Standards for Germany." Brussels: Regulatory Assistance Project. https://www.raponline.org/knowledge-center/considering-minimum-energy-performance-standards-for-germany/.

Surana, K., and S.M. Jordaan. 2019. "The Climate Mitigation Opportunity behind Global Power Transmission and Distribution." *Nature Climate Change* 9 (9): 660–65. doi:10.1038/s41558-019-0544-3.

Sward, J., N. Amerasinghe, A. Bunker, and J. Walker. 2021. "IMF Surveillance and Climate Change Transition Risks: Reforming IMF Policy Advice to Support a Just Energy Transition." Washington, DC: Bretton Woods Project and ActionAid USA. https://www.actionaidusa.org/publications/imf-surveillance-and-climate-change-transition-risks-reforming-imf-policy-advice-to-support-a-just-energy-transition/.

Swensson, L.F.J., and F. Tartanac. 2020. "Public Food Procurement for Sustainable Diets and Food Systems: The Role of the Regulatory Framework." *Global Food Security* 25 (June): 100366. doi:10.1016/j.gfs.2020.100366.

Sze, J.S., L.R. Carrasco, D. Childs, and D.P. Edwards. 2022. "Reduced Deforestation and Degradation in Indigenous Lands Pan-tropically." *Nature Sustainability* 5 (2): 123–30. doi:10.1038/s41893-021-00815-2.

Taibi, E., H. Blanco, R. Miranda, and M. Carmo. 2020. "Green Hydrogen Cost Reduction: Scaling Up Electrolysers to Meet the 1.5°C Climate Goal." Abu Dhabi: IRENA. https://www.irena.org/publications/2020/Dec/Green-hydrogen-cost-reduction.

Tang, C.K. 2021. "The Cost of Traffic: Evidence from the London Congestion Charge." *Journal of Urban Economics* 121 (January): 103302. doi:10.1016/j.jue.2020.103302.

Tanneberger, F., L. Appulo, S. Ewert, S. Lakner, N. Ó Brolcháin, J. Peters, and W. Wichtmann. 2021. "The Power of Nature-Based Solutions: How Peatlands Can Help Us to Achieve Key EU Sustainability Objectives." *Advanced Sustainable Systems* 5 (1): 2000146. doi:10.1002/adsu.202000146.

Taylor, M. 2019. "Norway's Wealth Fund Ditches 33 Palm Oil Firms over Deforestation." Reuters, February 28. https://www.reuters.com/article/us-norway-pension-palmoil-idUSKCN1QH1MR.

Taylor, M. 2020. "Energy Subsidies: Evolution in the Global Energy Transformation to 2050." Abu Dhabi: International Renewable Energy Agency. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Apr/IRENA_Energy_subsidies_2020.pdf.

Taylor, R., and C. Streck. 2018. "Ending Tropical Deforestation: The Elusive Impact of the Deforestation-Free Supply Chain Movement." Washington, DC: World Resources Institute. https://www.wri.org/publication/ending-tropical-deforestation-elusive-impact-deforestation-free-supply-chain-movement#:~:text=Supply%20Chain%20Movement-,Ending%20Tropical%20Deforestation%3A%20The%20Elusive%20Impact%20of,Deforestation%2DFree%20Supply%20Chain%20Movement&text=Hundreds%20of%20companies%20with%20exposure,have%20committed%20to%20addressing%20deforestation.

TCFD (Task Force on Climate-Related Financial Disclosures). 2021. *2021 Status Report*. Basel, Switzerland: TCFD. https://assets.bbhub.io/company/sites/60/2021/07/2021-TCFD-Status_Report.pdf.

Temmink, R.J.M., L.P.M. Lamers, C. Angelini, T.J. Bouma, C. Fritz, J. van de Koppel, R. Lexmond, et al. 2022. "Recovering Wetland Biogeomorphic Feedbacks to Restore the World's Biotic Carbon Hotspots." *Science* 376 (6593): eabn1479. doi:10.1126/science.abn1479.

Temple, J. 2021. "Carbon Removal Hype Is Becoming a Dangerous Distraction." *MIT Technology Review*, July 8. https://www.technologyreview.com/2021/07/08/1027908/carbon-removal-hype-is-a-dangerous-distraction-climate-change/.

Tenggren, S., J. Wangel, M. Nilsson, and B. Nykvist. 2016. "Transmission Transitions: Barriers, Drivers, and Institutional Governance Implications of Nordic Transmission Grid Development." *Energy Research & Social Science* 19 (September): 148–57. doi:10.1016/j.erss.2016.06.004.

Thacker, S., R. Pant, and J.W. Hall. 2017. "System-of-Systems Formulation and Disruption Analysis for Multi-scale Critical National Infrastructures." *Reliability Engineering & System Safety* 167 (November): 30–41. doi:10.1016/j.ress.2017.04.023.

Trancik, J.E. 2014. "Renewable Energy: Back the Renewables Boom." *Nature* 507 (7492): 300–302. doi:10.1038/507300a.

Transparency International. 2021. "2021 Corruption Perceptions Index." https://www.transparency.org/en/cpi/2021.

Tsan, M., S. Totapally, M. Hailu, and B.K. Addom. 2019. *The Digitalisation of African Agriculture Report, 2018–2019*. CTA (Technical Centre for Agricultural and Rural Cooperation) / Dalberg Advisors. https://cgspace.cgiar.org/handle/10568/101498.

Tubiello, F.N., C. Rosenzweig, G. Conchedda, K. Karl, J. Gütschow, P. Xueyao, G. Obli-Laryea, et al. 2021. "Greenhouse Gas Emissions from Food Systems: Building the Evidence Base." *Environmental Research Letters* 16 (6): 065007. doi:10.1088/1748-9326/ac018e.

Tubiello, F.N., K. Karl, A. Flammini, J. Gütschow, G. Obli-Laryea, G. Conchedda, X. Pan, et al. 2022. "Pre- and Post-production Processes Increasingly Dominate Greenhouse Gas Emissions from Agri-food Systems." *Earth System Science Data* 14 (4): 1795–1809. doi:10.5194/essd-14-1795-2022.

Turubanova, S., P.V. Potapov, A. Tyukavina, and M.C. Hansen. 2018. "Ongoing Primary Forest Loss in Brazil, Democratic Republic of the Congo, and Indonesia." *Environmental Research Letters* 13 (7): 074028. doi:10.1088/1748-9326/aacd1c.

Tyukavina, A., P. Potapov, M.C. Hansen, A.H. Pickens, S.V. Stehman, S. Turubanova, D. Parker, et al. 2022. "Global Trends of Forest Loss Due to Fire from 2001 to 2019." *Frontiers in Remote Sensing* 3. https://www.frontiersin.org/articles/10.3389/frsen.2022.825190.

UK Government. 2022. "Boiler Upgrade Scheme." March 18. https://www.gov.uk/guidance/check-if-you-may-be-eligible-for-the-boiler-upgrade-scheme-from-april-2022.

UKRI (UK Research and Innovation). 2021. "UK Invests over £30m in Large-Scale Greenhouse Gas Removal." https://www.ukri.org/news/uk-invests-over-30m-in-large-scale-greenhouse-gas-removal/.

UMAS (University Maritime Advisory Services). 2021. *A Strategy for the Transition to Zero-Emission Shipping*. London: UMAS. https://www.u-mas.co.uk/wp-content/uploads/2021/10/Transition-Strategy-Report.pdf.

UMAS. 2022a. *Closing the Gap*. London: Getting to Zero Coalition. https://www.u-mas.co.uk/wp-content/uploads/2022/01/Closing-the-Gap_Getting-to-Zero-Coalition-report.pdf.

UMAS. 2022b. "Momentum Builds for IMO's Future: Stronger Ambition and an Equitable Transition." UMAS (blog), June 10. https://www.u-mas.co.uk/momentum-builds-for-imos-future-stronger-ambition-and-an-equitable-transition/.

UNCCD (UN Convention to Combat Desertification). 2017. *Global Land Outlook*, 1st ed. Bonn, Germany: UNCCD. https://knowledge.unccd.int/sites/default/files/2018-06/GLO%20English_Full_Report_rev1.pdf.

UNCTAD (UN Conference on Trade and Development). 2019. *Trade and Development Report 2019: Financing a Global Green New Deal*. Geneva: UNCTAD. https://unctad.org/webflyer/trade-and-development-report-2019.

UNDESA (UN Department of Economic and Social Affairs). 2019. "World Population Prospects 2019." New York: UNDESA. https://population.un.org/wpp/.

UNDESA. 2021. "State of the World's Indigenous Peoples: Rights to Lands, Territories and Resources." New York: UNDESA. https://www.un.org/development/desa/indigenouspeoples/publications/state-of-the-worlds-indigenous-peoples.html.

UNDP (UN Development Programme). 2021. "The Peoples' Climate Vote." New York: UNEP; Oxford: University of Oxford. https://www.undp.org/publications/peoples-climate-vote.

UNEP (UN Environment Programme). 2017. "Global Review of Sustainable Procurement 2017." Nairobi: UNEP. https://wedocs.unep.org/bitstream/handle/20.500.11822/20919/GlobalReview_Sust_Procurement.pdf?sequence=1&amp%3BisAllowed=y%2C%20Factsheets%7C%7Chttps%3A//wedocs.unep.org/bitstream/handle/20.500.11822/20919/GlobalReview_Sust_Procurement_factsheet.pdf%3Fsequence%3D3&amp%3Bis=.

UNEP. 2020a. *Emissions Gap Report 2020*. Nairobi: UNEP. https://www.unep.org/emissions-gap-report-2020.

UNEP. 2020b. "Used Vehicles and the Environment." Nairobi: UNEP. https://www.unep.org/resources/report/global-trade-used-vehicles-report.

UNEP. 2021a. *2021 Global Status Report for Buildings and Construction*. Nairobi: UNEP. https://www.unep.org/resources/report/2021-global-status-report-buildings-and-construction.

UNEP. 2021b. *Adaptation Gap Report 2021: The Gathering Storm—Adapting to Climate Change in a Post-pandemic World*. Nairobi: UNEP. https://www.un-ilibrary.org/content/books/9789280738957.

UNEP. 2021c. *Emissions Gap Report 2021: The Heat Is On: A World of Climate Promises Not Yet Delivered*. Nairobi: UNEP. https://www.unep.org/resources/emissions-gap-report-2021.

UNEP. 2021d. *Food Waste Index Report 2021*. Nairobi: UNEP. https://www.unep.org/resources/report/unep-food-waste-index-report-2021.

UNEP. 2021e. "State of Finance for Nature." Nairobi: UNEP. https://www.unep.org/resources/state-finance-nature.

UNEP. 2021f. *Beating the Heat: A Sustainable Cooling Handbook for Cities*. Nairobi: UNEP. http://www.unep.org/resources/report/beating-heat-sustainable-cooling-handbook-cities.

UNEP. 2021g. "Global Methane Assessment: Benefits and Costs of Mitigating Methane Emissions." May 5. http://www.unep.org/resources/report/global-methane-assessment-benefits-and-costs-mitigating-methane-emissions.

UNEP. 2021h. "A Multi-billion-Dollar Opportunity: Repurposing Agricultural Support to Transform Food Systems." September 13. http://www.unep.org/resources/repurposing-agricultural-support-transform-food-systems.

UNEP. n.d. "Electric Two and Three Wheelers." https://www.unep.org/explore-topics/transport/what-we-do/electric-mobility/electric-two-and-three-wheelers.

UNEP and IEA. 2017. *Towards a Zero-Emission, Efficient, and Resilient Buildings and Construction Sector: Global Status Report 2017*. https://globalabc.org/sites/default/files/2020-09/2017%20GlobalABC%20GSR%20.pdf.

UNFCCC (UN Framework Convention on Climate Change). 1992. *United Nations Framework Convention on Climate Change*. https://unfccc.int/.

UNFCCC. 2009. Copenhagen Accord. https://unfccc.int/process-and-meetings/conferences/past-conferences/copenhagen-climate-change-conference-december-2009/cop-15/cop-15-decisions.

UNFCCC. 2015. *Adoption of the Paris Agreement*. https://unfccc.int/resource/docs/2015/cop21/eng/10a01.pdf.

UNFCCC. 2020. "Just Transition of the Workforce, and the Creation of Decent Work and Quality Jobs | UNFCCC." April 21. https://unfccc.int/documents/226460.

UNFCCC. 2021. *Glasgow Climate Pact*. https://unfccc.int/sites/default/files/resource/cma2021_10_add1_adv.pdf.

UN General Assembly. 2015. *Transforming Our World: The 2030 Agenda for Sustainable Development*. https://www.un.org/ga/search/view_doc.asp?symbol=A/RES/70/1&Lang=E.

UNIDO (UN Industrial Development Organization). 2021. "World's Largest Steel and Concrete Buyers Make Game-Changing Push for Greener Solutions." November 9. https://www.unido.org/news/worlds-largest-steel-and-concrete-buyers-make-game-changing-push-greener-solutions.

United Nations. 2015. "The 17 Goals: Sustainable Development Goals." https://sdgs.un.org/goals.

United Nations. 2022a. "Brief No. 1: Global Impact of War in Ukraine on Food, Energy and Finance Systems." UN Global Crisis Response Group on Food, Energy, and Finance. https://news.un.org/pages/wp-content/uploads/2022/04/UN-GCRG-Brief-1.pdf.

United Nations. 2022b. "Brief No. 2: Global Impact of the War in Ukraine: Billions of People Face the Greatest Cost-of-Living Crisis in a Generation." UN Global Crisis Response Group on Food, Energy, and Finance. https://news.un.org/pages/wp-content/uploads/2022/06/GCRG_2nd-Brief_Jun8_2022_FINAL.pdf.

United Nations. 2022c. "Brief No. 3: Global Impact of War in Ukraine: Energy Crisis." UN Global Crisis Response Group on Food, Energy, and Finance. https://news.un.org/pages/wp-content/uploads/2022/08/GCRG_3rd-Brief_Aug3_2022_FINAL.pdf.

Urge-Vorsatz, D., R. Khosla, R. Bernhardt, Y.C. Chan, D. Verez, S. Hu, and L.F. Cabeza. 2020. "Advances toward a Net-Zero Global Building Sector." *Annual Review of Environment and Resources* 45 (October): 227–69. doi:10.1146/ANNUREV-ENVIRON-012420-045843.

Urgewald. 2021. "Financiers of the Coal Industry." https://www.urgewald.org/sites/default/files/media-files/Release%20GCEL%20finance%20research.pdf.

U.S. CEQ (Council on Environmental Quality). 2021. *Council on Environmental Quality Report to Congress on Carbon Capture, Utilization, and Sequestration*. Washington, DC: U.S. CEQ. https://www.whitehouse.gov/wp-content/uploads/2021/06/CEQ-CCUS-Permitting-Report.pdf.

USDA (U.S. Department of Agriculture). n.d. "Conservation Compliance: Highly Erodible Land and Wetlands." Risk Management Agency. Accessed May 27, 2022. https://www.rma.usda.gov/en/Fact-Sheets/National-Fact-Sheets/Conservation-Compliance-Highly-Erodible-Land-and-Wetlands.

U.S. Department of State. 2021. *The Long-Term Strategy of the United States, Pathways to Net-Zero Greenhouse Gas Emissions by 2050*. November. https://unfccc.int/documents/308100.

U.S. DOE (Department of Energy). 2021. "Carbon Negative Shot." https://www.energy.gov/fecm/carbon-negative-shot.

U.S. EPA (Environmental Protection Agency). 2021. "EPA Facility Level GHG Emissions Data." https://ghgdata.epa.gov/ghgp/service/facilityDetail/2020?id=1005661&ds=E&et=&popup=true.

U.S. House of Representatives. 2020. Division C: Energy and Water Development and Related Agencies Appropriations Act, 2020. Washington, DC: U.S. House of Representatives. https://docs.house.gov/billsthisweek/20191216/BILLS-116HR1865SA-JES-DIVISION-C.pdf.

U.S. House of Representatives. 2021a. Division D: Energy and Water Development and Related Agencies Appropriations Act, 2021. https://docs.house.gov/billsthisweek/20201221/BILLS-116RCP68-JES-DIVISION-D.pdf.

U.S. House of Representatives. 2021b. H.R.3684—117th Congress (2021–2022): Infrastructure Investment and Jobs Act. https://www.congress.gov/bill/117th-congress/house-bill/3684/text.

U.S. House of Representatives. 2022a. Division D: Energy and Water Development and Related Agencies Appropriations Act, 2022. https://docs.house.gov/billsthisweek/20220307/BILLS-117RCP35-JES-DIVISION-D.pdf.

U.S. House of Representatives. 2022b. H.R.7434—117th Congress (2021–2022): Federal Carbon Dioxide Removal Leadership Act of 2022. Legislation, Congress, 2021–22, April 7. https://www.congress.gov/bill/117th-congress/house-bill/7434/text.

U.S. HUD (Department of Housing and Urban Development). 2021. "Zoning Reform in Minneapolis, Minnesota." *HUD User* (blog), March 18. https://www.huduser.gov/portal/elist/2021-Mar-18.html.

U.S. Senate. 2022. Inflation Reduction Act of 2022. https://www.democrats.senate.gov/imo/media/doc/inflation_reduction_act_of_2022.pdf.

van Ruijven, B.J., E. De Cian, and I. Sue Wing. 2019. "Amplification of Future Energy Demand Growth Due to Climate Change." *Nature Communications* 10 (1): 2762. doi:10.1038/s41467-019-10399-3.

Vass, T., P. Levi, A. Gouy, and H. Mandová. 2021. "Tracking Industry 2021." Paris: IEA. https://www.iea.org/reports/tracking-industry-2021.

Victor, D.G., F.W. Geels, and S. Sharpe. 2019. "Accelerating the Low Carbon Transition: The Case for Stronger, More Targeted and Coordinated International Action." Washington, DC: Brookings. https://www.brookings.edu/wp-content/uploads/2019/12/Coordinatedactionreport.pdf.

Volz, U. 2020. "Investing in a Green Recovery." Washington, DC: International Monetary Fund. https://www.imf.org/external/pubs/ft/fandd/2020/09/investing-in-a-green-recovery-volz.htm.

Volz, U., S. Akthar, K. Gallagher, S. Griffith-Jones, and J. Haas. 2020. "Debt Relief for a Green and Inclusive Recovery." Heinrich Böll Foundation; Center for Sustainable Finance, SOAS, University of London; Global Development Policy Center, Boston University. https://drgr.org/2020/11/16/report-debt-relief-for-a-green-and-inclusive-recovery/.

von Stechow, C., D. McCollum, K. Riahi, J.C. Minx, E. Kriegler, D.P. van Vuuren, J. Jewell, et al. 2015. "Integrating Global Climate Change Mitigation Goals with Other Sustainability Objectives: A Synthesis." *Annual Review of Environment and Resources* 40 (1): 363–94. doi:10.1146/annurev-environ-021113-095626.

Wainaina, P., P.A. Minang, J. Nzyoka, L. Duguma, E. Temu, and L. Manda. 2021. "Incentives for Landscape Restoration: Lessons from Shinyanga, Tanzania." *Journal of Environmental Management* 280 (February): 111831. doi:10.1016/j.jenvman.2020.111831.

Walker, N., S. Patel, F. Davis, S. Milledge, and J. Hulse. 2013. "Demand-Side Interventions to Reduce Deforestation and Forest Degradation." London: International Institute for Environment and Development. https://pubs.iied.org/13567iied.

Walker, W.S., S.R. Gorelik, A. Baccini, J.L. Aragon-Osejo, C. Josse, C. Meyer, M.N. Macedo, et al. 2020. "The Role of Forest Conversion, Degradation, and Disturbance in the Carbon Dynamics of Amazon Indigenous Territories and Protected Areas." *Proceedings of the National Academy of Sciences* 117 (6): 3015–25. doi:10.1073/pnas.1913321117.

Wang, X., and K. Lo. 2022. "Political Economy of Just Transition: Disparate Impact of Coal Mine Closure on State-Owned and Private Coal Workers in Inner Mongolia, China." *Energy Research & Social Science* 90 (August): 102585. doi:10.1016/j.erss.2022.102585.

Wappelhorst, S. 2021. "Update on Government Targets for Phasing Out New Sales of Internal Combustion Engine Passenger Cars." Berlin: International Council on Clean Transportation. https://theicct.org/publication/update-on-government-targets-for-phasing-out-new-sales-of-internal-combustion-engine-passenger-cars/.

Wappelhorst, S., and F. Rodríguez. 2021a. "Decarbonizing Bus Fleets: Global Overview of Targets for Phasing Out Combustion Engine Vehicles." Berlin: International Council on Clean Transportation. https://theicct.org/decarbonizing-bus-fleets-global-overview-of-targets-for-phasing-out-combustion-engine-vehicles/.

Wappelhorst, S., and F. Rodríguez. 2021b. "Global Overview of Government Targets for Phasing Out Internal Combustion Engine Medium and Heavy Trucks." Berlin: International Council on Clean Transportation. https://theicct.org/global-overview-of-government-targets-for-phasing-out-internal-combustion-engine-medium-and-heavy-trucks/.

Washington State Legislature. 2008. "Adoption of Statewide Goals to Reduce Annual per Capita Vehicle Miles Traveled by 2050." https://apps.leg.wa.gov/RCW/default.aspx?cite=47.01.440.

Way, R., M.C. Ives, P. Mealy, and J.D. Farmer. 2021. "Empirically Grounded Technology Forecasts and the Energy Transition." Institute for New Economic Thinking, Oxford University, September 14. https://www.inet.ox.ac.uk/publications/no-2021-01-empirically-grounded-technology-forecasts-and-the-energy-transition/.

Wee, S., M. Coffman, and S. La Croix. 2018. "Do Electric Vehicle Incentives Matter? Evidence from the 50 U.S. States." *Research Policy* 47 (9): 1601–10. doi:10.1016/j.respol.2018.05.003.

WEF (World Economic Forum). 2019. "How to Set Up Effective Climate Governance on Corporate Boards: Guiding Principles and Questions." Geneva: WEF. https://www.weforum.org/whitepapers/how-to-set-up-effective-climate-governance-on-corporate-boards-guiding-principles-and-questions.

WEF. 2020. "Clean Skies for Tomorrow: Sustainable Aviation Fuels as a Pathway to Net-Zero Aviation." Geneva: WEF. https://www.weforum.org/reports/clean-skies-for-tomorrow-sustainable-aviation-fuels-as-a-pathway-to-net-zero-aviation.

Weisse, M., and E.D. Goldman. 2017. "Global Tree Cover Loss Rose 51 Percent in 2016." World Resources Institute (blog), October 23. World Resources Institute. https://www.wri.org/insights/global-tree-cover-loss-rose-51-percent-2016.

Weisse, M., and E. Goldman. 2022. "Forest Pulse: The Latest on the World's Forests." *Global Forest Review* (blog). https://research.wri.org/gfr/latest-analysis-deforestation-trends.

Weisse, M., and P. Potapov. 2021. "How Tree Cover Loss Data Has Changed over Time." Global Forest Watch (blog), April 28. https://www.globalforestwatch.org/blog/data-and-research/tree-cover-loss-satellite-data-trend-analysis.

Welle, B., and S. Avelleda. 2020. "Safer, More Sustainable Transport in a Post-COVID-19 World." *Insights* (blog), April 23. World Resources Institute. https://www.wri.org/insights/safer-more-sustainable-transport-post-covid-19-world.

Westley, F., P. Olsson, C. Folke, T. Homer-Dixon, H. Vredenburg, D. Loorbach, J. Thompson, et al. 2011. "Tipping toward Sustainability: Emerging Pathways of Transformation." *AMBIO* 40 (7): 762–80. doi:10.1007/s13280-011-0186-9.

White House. 2021. "Justice40." https://www.whitehouse.gov/environmentaljustice/justice40/.

Wigneron, J.-P., L. Fan, P. Ciais, A. Bastos, M. Brandt, J. Chave, S. Saatchi, A. Baccini, and R. Fensholt. 2020. "Tropical Forests Did Not Recover from the Strong 2015–2016 El Niño Event." *Science Advances* 6 (6): eaay4603. doi:10.1126/sciadv.aay4603.

Williams, D.R., B. Phalan, C. Feniuk, R.E. Green, and A. Balmford. 2018. "Carbon Storage and Land-Use Strategies in Agricultural Landscapes across Three Continents." *Current Biology* 28 (15): 2500–505.e4. doi:10.1016/j.cub.2018.05.087.

Wilson, D., D. Blain, and J. Couwenberg. 2016. "Greenhouse Gas Emission Factors Associated with Rewetting of Organic Soils." *Mires and Peat*, no. 17 (April): 1–28. doi:10.19189/MaP.2016.OMB.222.

Wise, J., and D. Vennard. 2019. "It's All in a Name: How to Boost the Sales of Plant-Based Menu Items." *Insights* (blog), February 5. Washington, DC: World Resources Institute. https://www.wri.org/insights/its-all-name-how-boost-sales-plant-based-menu-items#.

Witohalls, S., and J. Riggall. 2018. "Power Poverty: The New Paradigm for Social and Economic Inequality of Electric Vehicles." *Stantec* (blog), March 15. https://www.stantec.com/en/ideas/topic/mobility/power-poverty-the-new-paradigm-for-social-and-economic-inequality-of-electric-vehicles.

Wolf, C., T. Levi, W.J. Ripple, D.A. Zárrate-Charry, and M.G. Betts. 2021. "A Forest Loss Report Card for the World's Protected Areas." *Nature Ecology & Evolution* 5 (4): 520–29. doi:10.1038/s41559-021-01389-0.

World Bank. 2014. "Motor Vehicles per 1000 Inhabitants vs GDP per Capita, 2014." Our World in Data. 2014. https://ourworldindata.org/grapher/road-vehicles-per-1000-inhabitants-vs-gdp-per-capita.

World Bank. 2021. "State and Trends of Carbon Pricing 2021." Washington, DC: World Bank. https://openknowledge.worldbank.org/handle/10986/35620.

World Bank. 2022a. "Carbon Pricing Dashboard." Washington, DC: World Bank. https://carbonpricingdashboard.worldbank.org/.

World Bank. 2022b. "State and Trends of Carbon Pricing 2022." Washington, DC: World Bank. https://openknowledge.worldbank.org/handle/10986/37455.

World Bank. 2022c. *Tracking SDG7: The Energy Progress Report*. Washington, DC: World Bank. https://trackingsdg7.esmap.org/data/files/download-documents/sdg7-report2022-full_report.pdf.

World Bank. n.d. "Employment in Agriculture (% of Total Employment) (Modeled ILO Estimate)." Accessed August 15, 2022. https://data.worldbank.org/indicator/SL.AGR.EMPL.ZS.

WGBC (World Green Building Council). 2021. "The Net Zero Carbon Buildings Commitment." https://worldgbc.org/thecommitment.

World Nuclear Association. 2022. "Nuclear Power in the World Today." June. https://world-nuclear.org/information-library/current-and-future-generation/nuclear-power-in-the-world-today.aspx.

World Steel Association. 2020. "Steel Statistical Yearbook 2020: Concise Version." https://worldsteel.org/wp-content/uploads/Steel-Statistical-Yearbook-2020-concise-version.pdf.

World Steel Association. 2021a. "Sustainability Indicators." https://worldsteel.org/steel-by-topic/sustainability/sustainability-indicators/.

World Steel Association. 2021b. "Total Production of Crude Steel: World Total 2021." https://worldsteel.org/steel-by-topic/statistics/annual-production-steel-data/P1_crude_steel_total_pub/CHN/IND.

Worthington, T.A., D.A. Andradi-Brown, R. Bhargava, C. Buelow, P. Bunting, C. Duncan, L. Fatoyinbo, et al. 2020. "Harnessing Big Data to Support the Conservation and Rehabilitation of Mangrove Forests Globally." *One Earth* 2 (5): 429–43. doi:10.1016/j.oneear.2020.04.018.

WRI (World Resources Institute). 2021. "European Union's Just Transition Mechanism: Transnational Funding and Support for a Just Transition." https://www.wri.org/update/european-unions-just-transition-mechanism-transnational-funding-and-support-just-transition.

WRI. 2022a. "Data and Methods." *Global Forest Review* (blog). https://research.wri.org/gfr/data-methods.

WRI. 2022b. "Forest Gain." *Global Forest Review* (blog). https://research.wri.org/gfr/forest-extent-indicators/forest-gain.

WRI. 2022c. "Forest Loss." *Global Forest Review* (blog). https://research.wri.org/gfr/forest-extent-indicators/forest-loss.

WRI. 2022d. "Forest Pulse." *Global Forest Review* (blog). https://research.wri.org/gfr/forest-pulse.

WRI. 2022e. "Indigenous and Community Forests." *Global Forest Review* (blog). https://research.wri.org/gfr/social-governance-issues-indicators/indigenous-community-forests.

WRI. 2022f. "Climate Watch Historical GHG Emissions." https://www.climatewatchdata.org/ghg-emissions.

Wu, E., and Z. Uddin. 2022. "As TCFD Comes of Age, Regulators Take a Varied Approach." Morgan Stanley Capital International, April 21. https://www.msci.com/www/blog-posts/as-tcfd-comes-of-age-regulators/03140250988.

WWA (World Weather Attribution initiative). 2022. "Climate Change Increased Heavy Rainfall, Hitting Vulnerable Communities in Eastern Northeast Brazil." London: WWA. https://www.worldweatherattribution.org/climate-change-increased-heavy-rainfall-hitting-vulnerable-communities-in-eastern-northeast-brazil/.

Wylie, L., A.E. Sutton-Grier, and A. Moore. 2016. "Keys to Successful Blue Carbon Projects: Lessons Learned from Global Case Studies." *Marine Policy* 65 (March): 76–84. doi:10.1016/j.marpol.2015.12.020.

Xie, Y., T. Dallmann, and R. Muncrief. 2022. "Heavy-Duty Zero-Emission Vehicles: Pace and Opportunities for a Rapid Global Transition." Washington, DC: Zero Emission Vehicles Transition Council. https://theicct.org/publication/hdv-zevtc-global-may22/.

Xu, J., P.J. Morris, J. Liu, and J. Holden. 2018. "PEATMAP: Refining Estimates of Global Peatland Distribution Based on a Meta-analysis." *CATENA* 160 (January): 134–40. doi:10.1016/j.catena.2017.09.010.

Xu, X., G. Jia, X. Zhang, W.J. Riley, and Y. Xue. 2020. "Climate Regime Shift and Forest Loss Amplify Fire in Amazonian Forests." *Global Change Biology* 26 (10): 5874–85. doi:10.1111/gcb.15279.

Xu, X., P. Sharma, S. Shu, T.-S. Lin, P. Ciais, F.N. Tubiello, P. Smith, et al. 2021. "Global Greenhouse Gas Emissions from Animal-Based Foods Are Twice Those of Plant-Based Foods." *Nature Food* 2 (9): 724–32. doi:10.1038/s43016-021-00358-x.

Yang, S., S. Hastings-Simon, and A.P. Ravikumar. 2022. "Global Liquefied Natural Gas Expansion Exceeds Demand for Coal-to-Gas Switching in Paris Compliant Pathways." *Environmental Research Letters* 17 (6): 064048. doi:10.1088/1748-9326/ac71ba.

Yildiran, B.M. 2022. "5 Ways to Accelerate Urban Cycling." Transformative Urban Mobility Initiative (blog), January 18. https://www.transformative-mobility.org/news/5-ways-to-accelerate-urban-cycling.

Yu, Z., J. Loisel, D.P. Brosseau, D.W. Beilman, and S.J. Hunt. 2010. "Global Peatland Dynamics since the Last Glacial Maximum." *Geophysical Research Letters* 37 (13). doi:10.1029/2010GL043584.

Yuki. 2021. "China's Hydrogen Market in 14th Five-Year Plan: Provincial Strategy Breakdown." *Energy Iceberg* (blog), March 10. https://energyiceberg.com/hydrogen-14th-fyp-provincial-strategy/.

Zerbe, S., P. Steffenhagen, K. Parakenings, T. Timmermann, A. Frick, J. Gelbrecht, and D. Zak. 2013. "Ecosystem Service Restoration after 10 Years of Rewetting Peatlands in NE Germany." *Environmental Management* 51 (6): 1194–1209. doi:10.1007/s00267-013-0048-2.

Zhang, C., O.B. Kazanci, R. Levinson, P. Heiselberg, B.W. Olesen, G. Chiesa, B. Sodagar, et al. 2021. "Resilient Cooling Strategies: A Critical Review and Qualitative Assessment." *Energy and Buildings* 251 (November): 111312. doi:10.1016/j.enbuild.2021.111312.

Zhang, R., and S. Fujimori. 2020. "The Role of Transport Electrification in Global Climate Change Mitigation Scenarios." *Environmental Research Letters* 15 (3): 034019. doi:10.1088/1748-9326/ab6658.

Zinecker, A., S. Sharma, C. Beaton, L. Merrill, and L. Sanchez. 2018. "Getting on Target: Accelerating Energy Access through Fossil Fuel Subsidy Reform." Winnipeg, Canada: International Institute for Sustainable Development Global Subsidies Initiative. https://www.iisd.org/publications/getting-target-accelerating-energy-access-through-fossil-fuel-subsidy-reform.

PHOTO CREDITS

Cover, William Gibson/Unsplashed; Pg. ii-vi, Annie Spratt/Unsplash; Pg. vi, Wind Denmark/Flickr.

Executive Summary:
Pg. 1, Lee Bosher/Flickr; Pg. 3, Friends of the Earth International/Flickr; Pg. 11, David Dodge/Flickr; Pg. 14, Nathan Wright/Unsplash; Pg. 16, Henry Sudarman/Flickr.

Methodology for Assessing Progress:
Pg. 21, Neil Palmer/Flickr; Pg. 23, This is Engineering/Flickr; Pg. 26, Abbie Trayler-Smith/Flickr.

Power:
Pg. 28, Hans Ott/Unsplashed; Pg. 29, International Monetary Fun/Flickr; Pg. 34, Chris Leboutillier/Unsplashed; Pg. 39, CGIAR System Organization/Flickr; Pg. 44, International Monetary Fund/Flickr.

Buildings:
Pg 45, Ricardo Gomez Angel/Unsplashed; Pg. 47, Adam Cohn/Flickr; Pg. 48, Christopher Burns/Unsplashed; Pg. 51, Scottish Government/Flickr; Pg. 52, Niall Kennedy/Flickr; Pg. 54, Graham Klingler/Unsplashed; Pg. 56, Andreas Brucker/Unsplashed; Pg. 57, Ashley/Flickr.

Industry:
Pg. 58, Mads Eneqvist; Pg. 59, Adam Cohn/Flickr; Pg. 62, Dale Matteson/Flickr; Pg. 68, Ant Rozetsky/Unsplash.

Transport:
Pg. 71, Ryoji Iwata/Unsplashed; Pg. 73, International Monetary Fund/Flickr; Pg. 75, Derek Lee/Unsplashed; Pg. 76, Maarten van den Heuvel/Unsplash; Pg. 77, Dr. Matthias Ripp/Flickr; Pg. 78, Climate Group/Flickr; Pg. 80, Michael Fousert/Unsplashed; Pg. 82, Ivan Bandura/Unsplashed; Pg. 84, William William/Unsplashed; Pg. 85, tokyoform/Flickr; Pg. 87, Skyler Smith/Unsplashed.

Forests and Land:
Pg. 95, USAID Biodiversity & Forestry/Flickr; Pg. 95, CIFOR/Flickr; Pg. 99, World Resources Institute/Flickr; Pg. 101, Geio Tischler/Unsplash; Pg. 103, UNDP Climate/Flickr; Pg. 105, NPS Climate Change Response/Flickr.

Food and Agriculture:
Pg. 115, Rod Waddington/Flickr; Pg. 116, Alliance of Bioversity International and CIAT/Flickr; Pg. 118, Eduardo Prim/Unsplashed; Pg. 120, David Stewart/Flickr; Pg. 122, Dean Hochman/Flickr; Pg. 124, Adam Cohn/Flickr; Pg. 125, UNICEF Ethiopia/Flickr; Pg. 126, CIFOR/Flickr; Pg. 127, CIFOR/Flickr; Pg. 128, Climate Change, Agriculture and Food Security/Flickr; Pg. 129, Tim Shepherd/Unsplashed; Pg. 130, Alliance of Bioversity International and CIAT/Flickr; Pg. 131, Alliance of Bioversity International and CIAT/Flickr; Pg. 132, Alliance of Bioversity International and CIAT/Flickr;

Technological Carbon Removal:
Pg. 133, Climateworks; Pg. 140, Pop Zebra/Unsplashed; Pg. 141, Climateworks.

Finance:
Pg. 142, UNclimatechange/Flickr; Pg. 143, Rettet den Regenwald e.V. (Rainforest Rescue)/Flickr; Pg. 145, UNclimatechange/Flickr; Pg. 150, Maria Lupan/Unsplash; Pg. 154, Rafael Matsunaga/Flickr; Pg. 157, Roy/Flickr.

Conclusion:
Pg. 159, The National Guard/Flickr; Pg. 160, Adam Cohn/Flickr.

Appendices:
Pg. 163, EJ Yao/Unsplashed

MAPS

Maps are for illustrative purposes and do not imply the expression of any opinion on the part of Bezos Earth Fund, Climate Action Tracker (including Climate Analytics and NewClimate Institute), ClimateWorks Foundation, the United Nations Climate Change High-Level Champions, and World Resources Institute, concerning the legal status of any country or territory or concerning the delimitation of frontiers or boundaries.

About Systems Change Lab

Systems Change Lab monitors, learns from, and mobilizes action toward the transformational shifts necessary to protect both people and the planet. Convened by World Resources Institute and Bezos Earth Fund, Systems Change Lab supports the United Nations Climate Change High-Level Champions and works with key partners and funders including Climate Action Tracker, 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

United Nations Climate Change High-Level Champions

The United Nations Climate Change High-Level Champions for COP26 and COP27—Mahmoud Mohieldin and Nigel Topping—build on the legacy of their predecessors to engage with nonstate actors and activate the "ambition loop" with national governments. Their work is fundamentally designed to encourage a collaborative shift across all of society towards a decarbonized economy, so that we can all thrive in a healthy, resilient, zero-carbon world. Mahmoud and Nigel have convened a team to help them deliver on this work through flagship campaigns, targeted stakeholder engagement, and leadership in systems transformation.

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 non-profit institute leading research on climate science and policy in relation to the 1.5°C limit in the Paris Agreement. It has offices in Germany, the United States, Togo, Australia, Nepal, and Trinidad and Tobago.

NewClimate Institute

NewClimate Institute is a non-profit institute established in 2014. NewClimate Institute supports research and implementation of action against climate change around the globe, covering the topics of international climate negotiations, tracking climate action, climate and development, climate finance, and carbon market mechanisms. NewClimate Institute aims at connecting up-to-date research with real world decision-making processes.

ClimateWorks Foundation

ClimateWorks Foundation is a global platform for philanthropy to innovate and accelerate climate solutions that scale. We deliver global programs and services that equip philanthropy with the knowledge, networks, and solutions to drive climate progress. Since 2008, ClimateWorks Foundation has granted over $1.3 billion to more than 600 grantees in over 50 countries.

Bezos Earth Fund

Bezos Earth Fund is Jeff Bezos's $10 billion commitment to fund scientists, activists, NGOs, and other actors that will drive climate and nature solutions. By allocating funds creatively, wisely, and boldly, the Bezos Earth Fund has the potential for transformative influence in this decisive decade. Funds will be fully allocated by 2030—the date by which the United Nations' Sustainable Development Goals must be achieved.

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.

SYSTEMS
CHANGE
LAB